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US EPA RECORDS CENTER REGION 5



467466

June 2, 2005

VIA FACSIMILE & CERTIFIED MAIL - RETURN RECEIPT REQUESTED

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Mr. Brian Kelly  
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U. S. Environmental Protection Agency  
Emergency Response Branch  
Region 5  
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Grosse Ile, Michigan 48138

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Assistant Regional Counsel  
U. S. Environmental Protection Agency  
77 W. Jackson Boulevard, C-14J  
Chicago, Illinois 60604-3590

**bodman**  
ATTORNEYS & COUNSELORS

Re: Unilateral Administrative Order Issued to CSX Transportation, Inc.  
Regarding the N-Forcer Site in Dearborn, Michigan  
Docket Number: [Not Decipherable]  
Date: May 17, 2005

Dear Messrs. Kelly and Krueger:

This letter is CSX Transportation, Inc.'s request that the administrative records for the site and for the § 106 order be supplemented with the following materials:

### Sampling Results

ARCADIS letter of February 5, 2005 reporting on soil sampling conducted by CSXT in November, 2004.. (USEPA already has a copy of that letter)

The "follow up letter" from the lab which performed the analysis of ARCADIS' November sampling, clarifying issues raised by USEPA at the May 27 meeting with CSXT. This letter is expected within 2 business days and will be submitted to USEPA as soon as it is received.

Full laboratory documentation for the ARCADIS November sampling. This documentation has been requested from the lab and will be submitted to USEPA within 5 business days.

Sampling data and full laboratory documentation for soil and air sampling conducted on May 24 and 25, 2005 by CSXT. The preliminary results were shared with USEPA on May 27. Summary data tables will be provided by close of business on June 3 with full laboratory documentation to follow as soon as it is available.

Full laboratory documentation for all soil and air sampling conducted by USEPA or its contractors at the site.

Mr. Brian Kelly  
Thomad Krueger, Esq.  
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All field reports and photographs made by USEPA and its contractors with regard to any sampling conducted at the site and all diagrams depicting the location of samples.

### **Risk Related Materials**

ASTDR's Toxicological Profile For Asbestos (September 2001). We assume USEPA has a copy but can provide a copy for the record if needed.

Department of Community Health, Press Release, *Past Workers at Dearborn Plant Were Exposed To Hazardous Asbestos Levels* (November 9, 2004) (enclosed)

ATSDR/Michigan Department of Community Health, PowerPoint presentation, Dearborn Michigan public information meeting, December, 2004 (enclosed)

### **Regulatory Status of Asbestos Materials<sup>1</sup>**

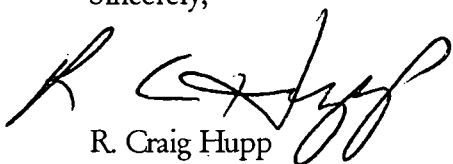
Wylie A.G., Verkouteren, J.R. Amphibole asbestos from Libby, Montana: Aspects of nomenclature. *Am Mineral* 85:1540-1542 (2000) (enclosed)

Bandli, B.R., An overview of the mining history, geology, mineralogy, and amphibole-asbestos health effects of the Rainy Creek igneous complex, Libby, Montana, U.S.A.; A case study in teaching environmental mineralogy. Presented at NAGT Workshop on Geology & Health, May 2004;  
<http://www.webpages.uidaho.edu/~mgunter/NAGT/manuscripts/BandliMS.pdf>  
(enclosed)

Vu, V.T., Regulatory Approaches to Reduce Human Health Risks Associated with Exposures to Mineral Fibers, published as Chapter 19 in *Health Effects of Mineral Dusts*, Guthrie, G.D. & Mosman, B.T., eds., Washington D.C., Mineralogical Society of America, 545-554.28 (enclosed)

Thank you very much for your consideration.

Sincerely,



R. Craig Hupp

c: Paul Kurzanski, Jeffrey Styron, Terri Rubis, Fredrick Dindoffer

<sup>1</sup> These materials are offered with regard to the question whether the forms of asbestos found in Libby ore are regulated and hence fall under CERCLA, not whether they pose a health hazard.



STATE OF MICHIGAN

DEPARTMENT OF COMMUNITY HEALTH  
LANSING

JENNIFER M. GRANHOLM  
GOVERNOR

JANET OLSZEWSKI  
DIRECTOR

FOR IMMEDIATE RELEASE  
November 9, 2004

CONTACT: T.J. Bucholz  
(517) 241-2112

## **Past Workers At Dearborn Plant Were Exposed To Hazardous Asbestos Levels**

Workers at the former W. R. Grace & Company vermiculite exfoliation plant in Dearborn – from the early 1950s to 1990 – were exposed to hazardous levels of asbestos, according to a public health consultation from the Michigan Department of Community Health (MDCH) and the federal Agency for Toxic Substances and Disease Registry (ATSDR).

Until 1990, the former W.R. Grace facility processed vermiculite – mined in Libby, Montana – that contained asbestos. ATSDR has linked some past exposures to Libby vermiculite to respiratory illnesses.

The consultation also indicated that those who lived with former W.R. Grace workers while Libby vermiculite was being processed at the plant also were exposed to asbestos. Workers may have carried home asbestos fibers on their hair and clothing, but the degree to which household members may have been exposed cannot be conclusively determined, according to MDCH officials.

MDCH and ATSDR found no indication that current workers on the property – employed by a tool and die shop – are being exposed to hazardous levels of asbestos. Some soil samples from the site, taken by the Environmental Protection Agency (EPA), show concentrations of asbestos at very low levels. Other samples failed to detect asbestos.

Officials also suspect that some former workers and residents took asbestos-contaminated waste rock home from the plant and used it around their homes (for example, for driveway and garden filler). People could still be exposed to small amounts of this asbestos today if any waste rock remains exposed and is disturbed (by foot or vehicle traffic, for example).

MDCH and ATSDR recommends that former workers and the household members who lived with them learn more about asbestos and see a doctor with expertise in asbestos-related lung diseases. “MDCH can help you learn more as well as provide assistance in locating such medical expertise,” said Erik R. Janus, toxicologist for the MDCH Bureau of Epidemiology.

The former W.R. Grace plant health consultation was done in cooperation with ATSDR and is part of that agency’s National Asbestos Exposure Review (NAER). Under the program, more than 200 sites around the United States that received vermiculite ore mined in Libby from the early 1920s until 1990 are being evaluated. More information about NAER is available online at <http://www.atsdr.cdc.gov/naer/index.html>.

MORE

The ATSDR/MDCH public health consultation is available for review at the Dearborn Public Library (16301 Michigan Avenue, Dearborn) or the Arab Community Center for Economic and Social Services (6450 Maple Street, Dearborn). It also is available on-line at <http://www.michigan.gov/mdch-toxics/> or <http://www.atsdr.gov/naer/dearbornmi>.

MDCH welcomes comments and information from community members about the health consultation and the site contamination. Questions and MDCH's responses will be published later in a separate document. A public availability session in Dearborn will be held in the near future with members of the MDCH, ATSDR and EPA present. The primary purpose of this meeting is to field questions, comments, and concerns regarding both the document and potential exposure to asbestos-contaminated vermiculite. Questions on the health consultation document must be submitted in writing to:

Erik R. Janus  
Division of Environmental and Occupational Epidemiology  
Bureau of Epidemiology  
Michigan Department of Community Health  
3423 N. Martin Luther King Jr. Blvd.  
P.O. Box 30195  
Lansing, MI 48909

For more information, community members may contact Erik Janus with the Michigan Department of Community Health, Bureau of Epidemiology toll-free at 800-648-6942, or via electronic mail at [januse@michigan.gov](mailto:januse@michigan.gov).

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# Asbestos Contamination at the former W.R. Grace/Dearborn Facility

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Michigan  
Department of  
Community Health

Erik R. Janus  
Brendan Boyle

# Who are the resource people?

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- *Michigan Department of Community Health (MDCH)* – Erik Janus, Brendan Boyle
- *Agency for Toxic Substances and Disease Registry (ATSDR)* – Mark Johnson, Michelle Watters
- *Environmental Protection Agency (EPA)* – Brian Kelly

# Why are we here tonight?

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- Present our partners and colleagues and local specialists
- Discuss the basic nature of the contamination at the former W. R. Grace facility
- Be available to answer your questions and concerns

# W.R. Grace/Zonolite Company

## 14300 Henn Street, Dearborn

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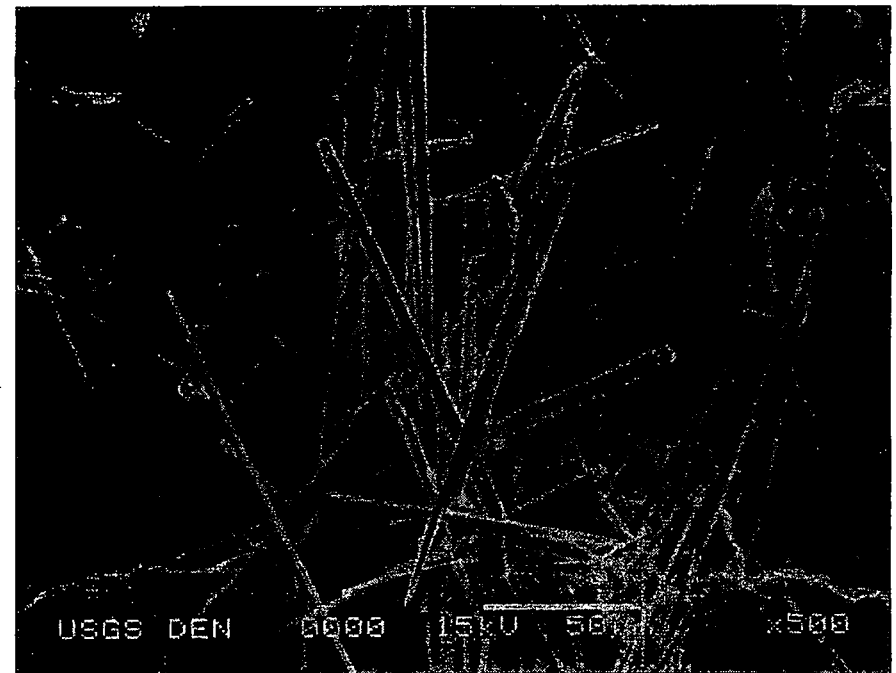
- Operated from 1950s to '89
- "Expanded" vermiculite ore from Libby, MT
- Ore was contaminated with asbestos
- ***DOES NOT*** process ore today



# Asbestos Facts

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- Naturally-occurring minerals
- Strong, flexible, heat-resistant needle-like fibers
- Used in a wide variety of manufactured goods
- Breathing asbestos fibers can increase your risk of cancer



# “Health Consultation” Conclusions

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- People who worked at the Grace facility prior to 1989 were consistently exposed to harmful levels of asbestos
- “Household contacts” (spouse, kids, etc.) were also likely exposed from fibers on the workers’ clothing, shoes, and/or hair

# “Health Consultation” Conclusions (cont’d)

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- Most people who live or work near the site today are generally not being exposed
- Some may be exposed under unique circumstances ...
  - ... such as frequent direct contact with contaminated soil
  - ... such as coming into contact with waste material brought home from the facility

# Could I have been exposed?

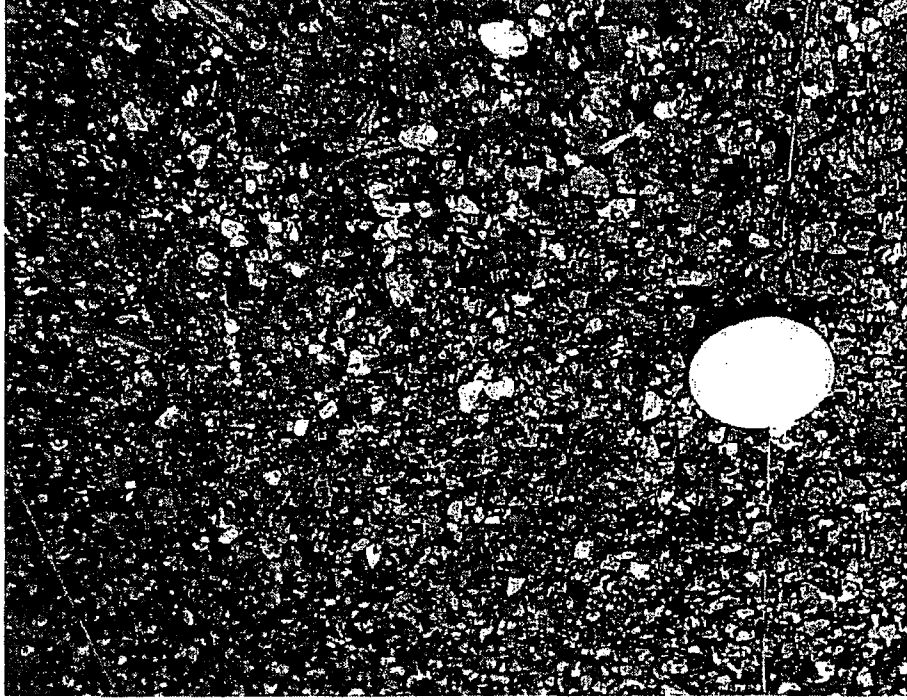
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- You **were** exposed if:
  - You worked at the facility prior to 1989 when it still processed vermiculite ore
  - You lived with someone who worked at the facility prior to 1989

# Could I have been exposed?

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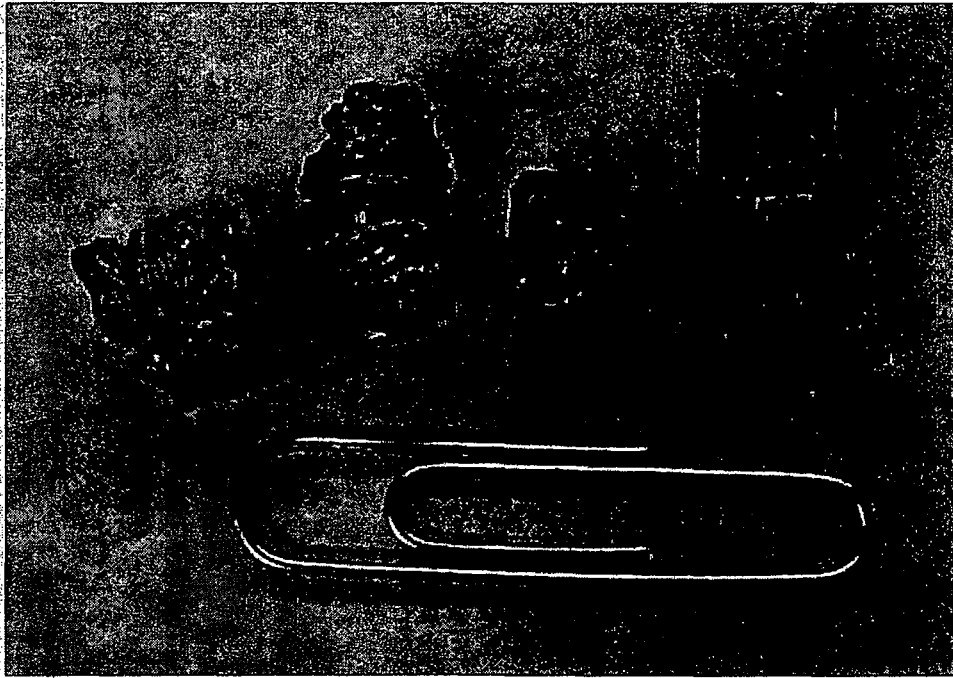
- You **probably were** exposed if:
  - You lived/worked near the site ***and*** had direct contact with ore, insulation material, waste material, or dust emissions from facility
  - You brought home ore, insulation material, or waste material from the facility to use as driveway, yard or garden filler



Vermiculite Ore

# Vermiculite Attic Insulation

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# Question and Answer time!

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We have provided several resources tonight to answer questions:

- MDCH
- EPA
- ATSDR
- Physician Resources (Doctors)



# Who can I contact for more information?

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- MDCH, Lansing – Erik Janus
  - 1-800-MI-TOXIC (800 648 6942)
  - [januse@michigan.gov](mailto:januse@michigan.gov)
- EPA, Grosse Ile – Brian Kelly
  - (734) 692 7684
- ATSDR, Chicago – Mark Johnson
  - (312) 886 0840

## Amphibole asbestos from Libby, Montana: Aspects of nomenclature

ANN G. WYLIE<sup>1</sup> AND JENNIFER R. VERKOUTEREN<sup>2,\*</sup>

<sup>1</sup>Laboratory for Mineral Deposits Research, Department of Geology, University of Maryland, College Park, Maryland, 20742, U.S.A.

<sup>2</sup>Chemical Science and Technology Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland, 20899, U.S.A.

### ABSTRACT

Richterite-asbestos and winchite-asbestos are not listed in the federal regulations governing asbestos. However, asbestiform winchite is found in the gangue at the Libby, Montana, vermiculite deposit, where asbestos-related diseases have been reported among the miners and millers. Changing amphibole nomenclature, uncertainties in  $\text{Fe}^{2+}/\text{Fe}^{3+}$ , and natural compositional variability result in samples of the asbestiform amphibole from Libby being variably classified as soda tremolite, richterite, sub-calcic actinolite, and winchite. A classification of winchite-asbestos is assigned for two samples of Libby asbestos analyzed for this report, consistent with the most recent International Mineralogical Association classification system. Although some of the unit-cell parameters and optical properties reported here are distinctive, others are very similar to the tremolite-actinolite series.

### INTRODUCTION

The U.S. Occupational Safety and Health Administration (OSHA) and the U.S. Environmental Protection Agency (EPA) have regulated asbestos since the early 1970s (summarized by Vu 1993). The current regulations specify chrysotile and the asbestiform habit of five amphiboles: tremolite, actinolite, anthophyllite, riebeckite (listed as crocidolite) and cummingtonite-grunerite (listed as amosite) (Title 40, Code of Federal Regulations, Part 61 and Part 763; Title 29, Code of Federal Regulations, Part 1910 and Part 1926<sup>1</sup>). These minerals were known at the time the regulations were first written to have been mined commercially as asbestos. Although there have been modifications to the regulations since they were first promulgated, most notably to clarify that cleavage fragments are not asbestos (Federal Register 1992), the minerals that are regulated have not changed. In particular, the sodic-calcic amphiboles winchite and richterite are not regulated.

An asbestiform amphibole occurs as a gangue mineral in the Zonolite<sup>®</sup> vermiculite ore body in Libby, Montana, which was mined from 1923 to 1990. Estimates of the abundance of the amphibole in the unprocessed ore range from 0 to  $\approx 5$  wt% (Atkinson et al. 1982). An elevated incidence of mesothelioma, the hallmark of asbestos exposure, has been reported among the miners and millers of Zonolite<sup>®</sup> in several studies that were summarized by Ross et al. (1993). In late 1999 and early 2000, many deaths alleged to be due to asbestos exposure in Libby were reported in the popular press, stimulating Congressional oversight (106<sup>th</sup> Congress 2000). Of particular significance for

the regulatory community is the identity of the asbestiform amphibole.

The asbestiform amphibole at Libby has been referred to under a variety of names, including tremolite, actinolite, soda tremolite, richterite, and winchite. The current nomenclature used in the popular press and by the residents of Libby is tremolite, or tremolite/actinolite. Deer et al. (1963) give an analysis of an amphibole from Libby (taken from Larson 1942) that they identify as "richterite (soda tremolite)."

In the amphibole classification system of Deer et al. (1963), Miyashiro's (1957) classification of the alkali amphiboles was generally adopted. However, of particular significance to the Libby amphibole, Deer et al. (1963) used the name richterite in place of soda tremolite, dividing tremolite from richterite at  $\text{NaCa}_{1.5}$ , (they considered winchite to be a subset of richterite). The International Mineralogical Association (IMA) classification (Leake 1978) continued the use of richterite in place of soda tremolite and added specific chemical parameters for distinguishing the actinolite series from richterite and for applying the name winchite. The parameters for richterite were  $^{\text{B}}(\text{Ca} + \text{Na}) \geq 1.34$  atoms per formula unit (apfu) and  $0.67 < ^{\text{B}}\text{Na} < 1.34$  apfu (classifying the amphibole as a member of the sodic-calcic group) and  $\text{Si} > 7.5$  apfu and  $^{\text{A}}(\text{Na} + \text{K}) \geq 0.5$  apfu. By the IMA 1978 classification scheme, winchite is also a member of the sodic-calcic group and is distinguished from richterite by  $^{\text{A}}(\text{Na} + \text{K}) < 0.5$  apfu. Members of the actinolite series belong to the calcic group and have  $^{\text{B}}(\text{Ca} + \text{Na}) \geq 1.34$  apfu and  $^{\text{B}}\text{Na} < 0.67$  apfu. Another relevant evolution in the nomenclature was the division between tremolite and actinolite; according to Deer et al. (1963), tremolite contained between 0 and 20% ferro-actinolite while according to the IMA, tremolite contained no more than 10% ferro-actinolite. The most recent nomenclature changes in Deer et al. (1997) and the revised IMA classification (Leake et al. 1997) changed the positions of the subdivisions to fit a 50% rule. Under these changes,  $^{\text{B}}(\text{Na} +$

<sup>1</sup>Regulations dealing with asbestos can be obtained through the websites maintained by OSHA ([www.osha.gov](http://www.osha.gov)) and the EPA ([www.epa.gov](http://www.epa.gov)).

\* E-mail: [jennifer.verkouteren@nist.gov](mailto:jennifer.verkouteren@nist.gov)

Ca)  $\geq 1.0$  apfu is now used to define the calcic and sodic-calcic groups, and the calcic group has  $^{\text{B}}\text{Na} < 0.50$  apfu.

## RESULTS

Two samples of asbestiform amphibole from Libby were analyzed following the experimental procedures detailed in Verkouteren and Wylie (2000). Chemical compositions, cell parameters, and optical properties are given in Table 1. One of the samples had been in our collection for several years; the other was obtained recently. Sample 1 is relatively pure, loose fiber and sample 2 was collected from the mine dump and is composed primarily of asbestiform amphibole. In both cases, the fibers are light green and asbestiform. The wt% Fe (analyzed as FeO) was converted to formula proportions of cations assuming first all  $\text{Fe}^{2+}$  and then all  $\text{Fe}^{3+}$ . It seems likely that at least some portion of the iron is trivalent, as more than 8.0 apfu Si cannot be accommodated in the tetrahedral sites. Hence, the "true" formulae must lie somewhere between these two extremes.

Because  $^{\text{B}}(\text{Na} + \text{Ca}) \geq 1.0$  apfu this amphibole is either a sodic-calcic or a calcic amphibole. If all the iron is  $\text{Fe}^{2+}$ , then  $^{\text{B}}\text{Na} = 0.63$  or  $0.61$  apfu, and according to Miyashiro (1957) the amphibole should be called soda tremolite. According to Deer et al. (1963), it would probably be richterite. According to Leake (1978), it would be sub-calcic actinolite, and according to Deer et al. (1997) and Leake et al. (1997), it would be winchite. If all the iron is  $\text{Fe}^{3+}$ ,  $^{\text{B}}\text{Na}$  increases to 0.75 or 0.67 apfu and according to Leake (1978), Deer et al. (1997) and Leake et al. (1997), it would be winchite. The chemical composition of the Libby amphibole as reported by Larson (1942) corresponds to a current classification of richterite.

Deer et al. (1963) chose  $\text{NaCa}_{1.5}$  as the dividing line between richterite and tremolite because it was consistent with a

"relatively sudden" change in optical properties, specifically a decrease in birefringence, stronger pleochroism, lower indices of refraction, and smaller optic axial angle. The refractive indices given in Table 1 are different for the two samples, consistent with the change in  $1 - \text{Mg}/(\text{Mg} + \text{Fe} + \text{Mn})$ . Comparison of the optical properties to those of the actinolite series (Verkouteren and Wylie 2000) indicates that, for both samples,  $n_{\alpha}$  is high and  $n_{\gamma}$  is low, although not statistically outside the population of actinolite samples. The birefringence given in Table 1 is much lower than any actinolite sample in Verkouteren and Wylie (2000) and is a clear outlier; this is also true for the birefringence of the Libby amphibole given by Larson (1942). No difference exists between the optic axial angle given in Table 1 and the actinolite series; however, the optic axial angle for the Libby amphibole reported by Larson (1942) is distinctly smaller than that of corresponding actinolites.

Comparison of the lattice parameters to those of the actinolite series (Verkouteren and Wylie 2000) indicates that, for both samples,  $a$  and  $c$  are at or within the 95% prediction limits for actinolite, but  $b$  is outside the lower 95% prediction limit by more than  $0.025 \text{ \AA}$ . The values of  $a$  are high given a Ca value of 1.3 apfu; these samples would fall into an anomalous region in the actinolite series where  $a$  and Ca are positively correlated (Verkouteren and Wylie 2000), and we would predict an  $a$  of  $9.83 \text{ \AA}$  or lower. The values of  $\beta$  for the Libby samples are consistent with the actinolite series and the positive correlation of  $\beta$  and Ca. The potassian winchite-asbestos described by Wylie and Huggins (1980) has a larger  $a$  dimension, a smaller  $b$  dimension, and the same  $c$  dimension when compared with the actinolite series. Similarly, the three non-Ti bearing richterites in Oberti et al. (1992) have larger  $a$  dimensions, smaller  $b$  dimensions, and the same  $c$  dimensions when compared to the actinolite series.

TABLE 1. Chemical composition, optical properties, and cell parameters of 2 samples of winchite-asbestos, Libby, Montana. (1 $\sigma$  errors in parentheses)

Oxide	wt%			apfu $\Sigma$ , all $\text{Fe}^{2+}$		apfu $\Sigma$ , all $\text{Fe}^{3+}$	
	Sample 1*	Sample 2†		Sample 1	Sample 2	Sample 1	Sample 2
$\text{SiO}_2$	56.6(4)	56.1(2)	Si	8.04	8.01	7.92	7.92
$\text{TiO}_2$	n.d.	n.d.	$^{\text{IV}}\text{Al}$	—	—	0.08	0.07
$\text{Cr}_2\text{O}_3$	n.d.	n.d.	$\Sigma\text{T}$	8.04	8.01	8.00	8.00
$\text{Al}_2\text{O}_3$	0.5(1)	0.4(2)	$^{\text{VI}}\text{Al}$	0.09	0.07	0.01	—
FeO	6.0(6)	4.2(4)	Mg	4.28	4.45	4.21	4.41
MnO	0.1(0)	0.3(3)	Fe	0.72	0.50	0.71	0.50
MgO	20.2(5)	21.0(4)	Mn	0.01	0.03	0.01	0.03
CaO	8.3(10)	8.8(2)	$\Sigma\text{C}$	5.10	5.05	4.94	4.94
$\text{Na}_2\text{O}$	3.2(8)	3.4(2)	ex. C	0.10	0.05	—	—
$\text{K}_2\text{O}$	0.7(1)	0.8(2)	Ca	1.27	1.34	1.25	1.33
Total	95.6	95.0	$^{\text{B}}\text{Na}$	0.63	0.61	0.75	0.67
			$\Sigma\text{B}$	2.00	2.00	2.00	2.00
			$^{\text{A}}\text{Na}$	0.25	0.33	0.12	0.26
			$^{\text{A}}\text{K}$	0.13	0.15	0.13	0.15
			$\Sigma\text{A}$	0.38	0.48	0.25	0.41
			$1 - \text{Mg}/(\text{Mg} + \text{Fe} + \text{Mn})$	0.15	0.11	—	—

Notes: optical properties: Sample 1:  $n_{\alpha} = 1.621(1)$ ,  $n_{\beta} = 1.631(1)$ ,  $n_{\gamma} = 1.637(1)$ ,  $c\wedge Z = 15.8(0.5)^{\circ}$ . Sample 2:  $n_{\alpha} = 1.618(1)$ ,  $n_{\beta} = 1.628(1)$ ,  $n_{\gamma} = 1.634(1)$ ,  $c\wedge Z = 15.8(0.5)^{\circ}$ .  $\delta\ddagger = 0.016$ ,  $2V_{\gamma}\ddagger = 104.9$ .

Cell dimensions: Sample 1:  $a = 9.855(1) \text{ \AA}$ ,  $b = 18.032(1) \text{ \AA}$ ,  $c = 5.288(3) \text{ \AA}$ ,  $\beta = 104.54(2)^{\circ}$ . Sample 2:  $a = 9.861(2) \text{ \AA}$ ,  $b = 18.003(5) \text{ \AA}$ ,  $c = 5.276(6) \text{ \AA}$ ,  $\beta = 104.37(4)^{\circ}$ .

\* Average of 6 analyses.

† Average of 3 analyses.

§ Calculated on the basis of 23 O atoms.

‡ Calculated from the measured refractive indices.

## DISCUSSION

The composition of the Libby asbestiform amphibole as given in Table 1 is consistent with an identification of winchite-asbestos, based on Leake et al. (1997). The samples can be identified as winchites despite the uncertainty in site occupancies resulting from the unknown oxidation state of Fe. The *b* lattice dimension and the birefringence are consistent with what is known about winchite (and richterite) and are distinct from actinolite. Ross et al. (1993) report that both tremolite and richterite asbestos fibers were found in a specimen of Libby vermiculite. Our two samples were collected approximately ten years apart, and probably from different areas in the mine, and both are winchites, although our sample 2 is close to richterite in composition ( $\Sigma A = 0.48$  to  $0.41$  apfu). Given the fact that the Libby amphibole reported by Larson (1942) is a richterite, it is possible that the amphibole composition ranges from winchite to richterite, and possibly to actinolite, throughout the vermiculite deposit. Asbestiform winchite and richterite are also known from other localities, where they are similarly associated with the alteration of alkali igneous rocks (Wylie and Huggins 1980; Deer et al. 1997).

It is unfortunate that a regulatory decision could hinge on such details as the amount of  $^8\text{Na}$  and the choice of classification scheme. While the distinctions among amphiboles are important from a scientific standpoint, they do not add significantly to the regulatory terminology unless they are correlated with risk assessment. There are data that show differences in disease potential among different minerals with similar morphology, such as between talc and tremolite (Guthrie and Mossman 1993), but it is clear that the asbestiform winchite in Libby, Montana poses a health threat (106<sup>th</sup> Congress 2000). From an analytical standpoint, the identification of the specific asbestiform mineral is necessary for complete characterization of the asbestos component in any sample. The regulatory requirement to identify the mineral can be addressed by providing reference values for known asbestiform amphiboles, which was, in part, the impetus behind the study described in Verkouteren and Wylie (2000) and the current note. It would be reasonable for the regulations to be revised to provide a broader description of asbestiform amphiboles to avoid similar hair-splitting problems in the future.

## ACKNOWLEDGEMENTS

We thank Laura Kuzel and Robert Nolan for providing samples.

## REFERENCES CITED

- 106<sup>th</sup> Congress (2000) Federal, State, and Local Response to Public Health and Environmental Conditions from Asbestos Contamination in Libby, Montana (Full committee field hearing). Statements From Hearings Held 106<sup>th</sup> Congress, Second Session, U.S. Senate Committee on Environment and Public Works, February 16, 2000. [http://www.senate.gov/~epw/stml\\_106.htm#02-16-00](http://www.senate.gov/~epw/stml_106.htm#02-16-00)
- Atkinson, G.R., Rose, D., Thomas, K., Jones, D., Chatfield, E., and Goings, J. (1982) Collection, analysis and characterization of vermiculite samples for fiber content and asbestos contamination. Midwest Research Institute report for the U.S. Environmental Protection Agency, Project 4901-A32 under EPA Contract 68-01-5915, Washington, D.C.
- Deer, W.A., Howie, R.A., and Zussman, J. (1963) Rock-forming minerals, volume 2. Chain silicates, 377 p. Longmans, London.
- (1997) Rock-forming minerals, volume B, Double chain silicates, 2<sup>nd</sup> Ed., 764 p. The Geological Society, London.
- Federal Register (1992) Occupational Exposure to Asbestos, Tremolite, Anthophyllite, and Actinolite. FR 57:24310, June 8, 1992.
- Guthrie, Jr. G.D. and Mossman, B.T. (1993) Merging the geological and biological sciences: An integrated approach to the study of mineral-induced pulmonary diseases. In Mineralogical Society of America Reviews in Mineralogy, 28, 1–5.
- Larson, E.S. (1942) Alkaline rocks of Iron Hill, Gunnison County, Colorado. U.S. Geological Survey, Prof. Paper No. 97A.
- Leake, B.E. (1978) Nomenclature of amphiboles. American Mineralogist, 63, 1023–1052.
- Leake, B.E., Woolley, A.R., Arps, C.E.S., Birch, W.D., Gilbert, M.C., Grice, J.D., Hawthorne, F.C., Kato, A., Kisch, H.J., Krivovichev, V.G., Linthout, K., Laird, J., Mandarino, J.A., Maresch, W.V., Nickel, E.H., Rock, N.M.S., Schumacher, J.C., Smith, D.C., Stephenson, N.C.N., Ungaretti, L., Whittaker, E.J.W., and Youshi, G. (1997) Nomenclature of amphiboles: Report of the subcommittee on amphiboles of the International Mineralogical Association, Commission on new minerals and mineral names. American Mineralogist, 82, 1019–1037.
- Miyashiro, A. (1957) The chemistry, optics and genesis of the alkali-amphiboles. Journal of the Faculty of Science University Tokyo, Section 2, 11, 57–83.
- Oberti, R., Ungaretti, L., Cannillo, E. and Hawthorne, F.C. (1992) The behavior of Ti in amphiboles: I. Four- and six-coordinate Ti in richterite. European Journal of Mineralogy, 4, 425–439.
- Ross, M., Nolan, R.P., Langer, A.M., and Cooper, W.C. (1993) Health effects of mineral dusts other than asbestos. In Mineralogical Society of America Reviews in Mineralogy, 28, 361–407.
- Verkouteren, J.R. and Wylie, A.G. (2000) The tremolite-actinolite-ferro-actinolite series: Systematic relationships among cell parameters, composition, optical properties, and habit, and evidence of discontinuities. American Mineralogist, 85, 1239–1254.
- Vu, V.T. (1998) Regulatory approaches to reduce human health risks associated with exposure to mineral fibers. In Mineralogical Society of America Reviews in Mineralogy, 28, 545–554.
- Wylie, A.G. and Huggins, C.W. (1980) Characteristics of a potassic winchite-asbestos from the Allamoore Talc District, Texas. Canadian Mineralogist, 18, 101–107.

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**An overview of the mining history, geology, mineralogy, and amphibole-asbestos health effects of the Rainy Creek igneous complex, Libby, Montana, U.S.A.: A case study in teaching environmental mineralogy**

(modified from Bandli, B. R. (2002) Characterization of amphibole and amphibole-asbestos from the former vermiculite mine at Libby, Montana, U.S.A., M.S. Thesis, University of Idaho, Moscow, Idaho, U.S.A.)

**ABSTRACT**

The Rainy Creek igneous complex is an alkaline-ultramafic igneous intrusion in Lincoln County, Montana and is locally known as Vermiculite Mountain. Hydrothermal alteration and extensive weathering of the ultramafic units resulted in the formation of a rich deposit of vermiculite that was mined for 67 years and used in numerous consumer products in its expanded form sold under the trade name Zonolite. Later intrusions of alkaline magmas caused hydrothermal alteration of the pyroxenes resulting in formation of amphiboles. Approximately one-half of the amphiboles occur in the asbestiform habit and are associated with pulmonary diseases in former miners and mill workers. Identification of these amphibole minerals received little attention, but recent work shows the mineral species, mainly winchite and richterite, are not any of the asbestos species currently regulated by government agencies.

Articles in the popular press published late in 1999 stated there were increased risks of asbestos-related diseases among the former vermiculite miners, and a recent study by the Agency for Toxic Substances and Disease Registry has shown that residents of Libby also appear to have developed asbestos-related pulmonary diseases at a higher rate than the general public. Since November of 1999, the United States Environmental Protection Agency has been involved in the cleanup of asbestos contaminated sites in and around Libby associated with the mining and processing of vermiculite. On a much larger scale, are issues surrounding the possible remediation of 10-20 million homes in the U.S.A. that contain Zonolite insulation at an estimated cost exceeding \$10,000,000,000.

**INTRODUCTION**

This paper is an overview of the past 90 years of scientific research directed at multiple aspects of the former vermiculite mine near Libby, Montana. During its operation it was the largest producer of vermiculite in the world. Unfortunately the ore shipped from the mine contained a small percentage of amphibole-asbestos. The many issues surrounding Libby are introduced with the hope of providing background information to use Libby as a case study in teaching environmental mineralogy. Gunter (1994, 1999) presented similar articles on the environmental concerns of asbestos and quartz, and Lang (1998) suggested such issues provide our students case studies to examine the societal significance of mineralogy. Libby, and the former mine site, were basically unheard of before November 1999; however, since then issues surrounding Libby have garnering national press, are causing modifications in asbestos regulations, may result in billions of dollars of remediation costs, and are causing fear among millions of U.S. homeowners.

The first examination of the Rainy Creek igneous complex (RCC) was during gold explorations in the late 19<sup>th</sup> century. Pardee and Larsen (1929) began work in the area exploring the quartz veins in 1911. It was these early explorations, particularly by E.N. Alley, who observed exfoliation of vermiculite in the roof of exploration audits, which led to the discovery and large-scale mining of the vermiculite deposits in the area of Rainy Creek (Pardee and Larsen, 1929). (See Table 1 for timeline of important events.) During the 1920's, the Zonolite Company developed the deposit, and uses for exfoliated (expanded) vermiculite led to increased production. W.R. Grace Corporation purchased the mine from the Zonolite Company in 1963 and continued producing expanded vermiculite for its products such as Zonolite insulation and Monokote fireproofing, bulking agents, absorbents, and soil amendments. They increased production, and eventually the mine at Libby was the largest source of vermiculite worldwide. Along with the mine at Libby (Figures 1 A-C), W.R. Grace also operated an export facility and local expansion facilities (until 1990). The mine at Libby ceased operation in 1990. The vermiculite ore is contaminated with varying amounts of amphibole-asbestos (Figures 1 D-F), which formed as a result of hydrothermal alteration of pyroxene minerals. MEG collected geological and mineralogical samples from the former W.R. Grace vermiculite mine in October of 1999. Photographs in Figure 1 were also taken at that time. The crystal chemistry and morphology of these samples are discussed in Gunter et al. (2003). Since the involvement of the EPA in the asbestos cleanup, access to the former mine site has become extremely difficult.

Several epidemiological studies have documented the toxicity of the amphibole-asbestos minerals in the RCC. However, the species of amphibole has been misidentified as tremolite-asbestos in these studies. Recent work by Wylie and Verkouteren (2000) and Gunter et al. (2003) shows that the amphibole minerals are actually winchite and richterite. The asbestos minerals in the RCC appear to have significant effects on humans. The incidence of asbestosis, mesothelioma, and lung cancer is high in former mine workers, particularly those employed in the early unregulated workplace. The Agency for Toxic Substances and Disease Registry (ATSDR 2001) presented data that showed a significant number of individuals who lived in Libby and did not work in the mining or processing of vermiculite, show symptoms of diseases related to asbestos exposure. Currently, the United States Environmental Protection Agency (EPA) is proposing to list mining and milling operation sites in Libby as a Superfund site.

## **MINING HISTORY**

Mining and processing of vermiculite from the RCC continued uninterrupted from 1923 to 1990 (Table 1). E.N. Alley was the first individual to exploit the RCC vermiculite deposit in 1923. The incorporation of the Universal Zonolite Insulation Company and the Vermiculite and Asbestos Company were the first commercial ventures of the vermiculite deposits at Libby. In 1948, these two companies merged to become the Zonolite Company.

The processes involved in mining and milling the vermiculite did not change much over the lifespan of the mine (Table 1). Initially, vermiculite ore was removed from underground workings, but eventually surface mining methods (Figures 1 B & C) were

employed. The ore was generally very weathered and could be removed without blasting, but blasting was occasionally necessary. The mine was a large open pit that eventually covered several hundred acres (Figures 1 A & B and Figure 2). Ore was hauled to a transfer point on the west end of the mine (USEPA, 2001), where it was passed through a grizzly to remove the coarse fractions, and the remaining ore was transferred by conveyor to the concentrating/loading facility on the Kootenai River at the mouth of Rainy Creek (Figure 3) (Boettcher, 1963). In the mill, the vermiculite was concentrated through a dry beneficiation process until 1954, when a wet beneficiation process was developed. Both processing methods were used until 1974 when the dry process was discontinued. Next, the concentrate was screened into 5 grades based on particle size. A portion of the vermiculite concentrate was sent to an exfoliating and export plant in Libby. However, the majority of the vermiculite concentrate was transferred across the Kootenai River by conveyor for shipment by rail to expansion facilities across the United States (USEPA, 2001).

At the expanding facilities the vermiculite was heated in kilns to approximately 1100° C for a few seconds (Bassett, 1959). This rapid heating caused the water in the vermiculite structure to vaporize, forcing the layers apart and creating the useable product (Figure 4). W.R. Grace marketed the majority of the expanded vermiculite originating from its Libby mine as Zonolite insulation. The mining and processing operations at Libby were very dusty by nature, and owners of the mine and various regulatory agencies worked to reduce the levels of dust exposure. Regulations regarding acceptable limits of the amount of airborne asbestos fiber workers can be exposed to are listed in Table 2, and these limits decreased over time.

## GEOLOGY

The RCC is an alkaline-ultramafic igneous complex in Lincoln County, Montana seven miles northeast of Libby and is locally known as Vermiculite Mountain (Figure 5). The RCC lies in the basin of Rainy Creek and is much less resistant to erosion than the surrounding Belt series metamorphic rocks. The contact between the ultramafic and metamorphic units is topographically expressed in a significant increase in slope in the metamorphic units. There is also a significant decrease in the density of coniferous vegetation growing in soils over the ultramafic units (Boettcher, 1963). The rocks of the complex, where not exposed by mining, are covered by till (Larsen and Pardee, 1929). The geology of the RCC has been studied by several individuals: Goranson (1927), Pardee and Larsen (1929), Larsen and Pardee (1929), Kriegel (1940), Bassett (1959), Boettcher (1963, 1966a, 1966b, 1967), and is currently being studied by the United States Geological Survey (Meeker et al., 2003). Boettcher provides the most detailed and most recently published geologic and mineralogical information on the RCC.

The rocks of this igneous complex formed by intrusion into the Precambrian Belt series (Wallace Formation) (Figure 5). The magma intruded into the axis of a slightly southeasterly plunging syncline (Figure 5). The rocks of the RCC consist of biotite, biotite pyroxenite, magnetite pyroxenite, syenite, trachyte, phonolite, and granite (Boettcher, 1967). Workers prior to Boettcher (1967) collectively described the biotite pyroxenite and magnetite pyroxenite as pyroxenite. The main body of the complex is a

stock composed predominantly of biotite pyroxenite, magnetite pyroxenite, and biotitite. A large, irregularly shaped body of altered nepheline syenite crosscuts the pyroxenites (Figure 5). All of these units are crosscut by trachyte and phonolite dikes, which are, in turn, cut by granitic dikes (Boettcher, 1963).

**Biotitite:** The central and topographically highest unit of the complex is a coarse-grained biotitite that comprises approximately 5% of the intrusion. The biotitite is composed almost entirely of anhedral books of biotite that are generally larger than 10 cm and show no preferred orientation (Boettcher, 1966a). The biotitite was thought by Boettcher to have formed near the roof of the magma chamber in the presence of higher concentrations of alkali metals, metal sulfides, and volatiles relative to the surrounding pyroxenites. Larsen and Pardee (1929) mentioned a "biotite rock," but it does not appear to be the biotitite unit described by Boettcher (1967). The Larsen and Pardee (1929) "biotite rock" was described as being almost entirely altered to vermiculite, whereas the biotitite described by Boettcher is composed of unaltered biotite with only small amounts of vermiculite.

Feldspars occur as wedges between books of biotite and make up less than 10% of the rock. Small amounts (<2%) of pyrite and calcite occur as secondary alteration products. Calcite is evenly distributed throughout the biotitite as a secondary alteration product of the biotite (Boettcher, 1966a). The contact between the biotitite and the biotite pyroxenite is gradational over 3 m. The contact zone is also expressed in a compositional change, where feldspar content decreases to zero while diopside and vermiculite content increase significantly (Boettcher, 1967).

**Biotite pyroxenite:** The biotite pyroxenite completely surrounds and has a gradational contact with the inner biotitite (Figure 5). The biotite pyroxenite makes up approximately 20% of the intrusion (Boettcher, 1967). In hand sample, it is dark green, and although friable (Fig 1D), most of the diopside appears unaltered. The biotite pyroxenite ranges in size from <1 mm to >10 cm, and is composed of variable amounts of clinopyroxene (diopside), biotite, vermiculite, and hydrobiotite. This unit was the source of all the mineable vermiculite, and vermiculite content varies significantly, but on average is 25 wt.% (Boettcher, 1966a). Unaltered biotite can be found locally within the biotite pyroxenite. Bassett (1959) observed areas where pyroxene crystals were horizontally oriented but were crosscut by veins of fine-grained pyroxenite where the pyroxenes were oriented vertically. This would indicate some sort of vertical flow of the magma prior to complete crystallization, according to Bassett (1959). Apparently, this feature does not occur over large areas of pyroxene-bearing units and Boettcher (1966a) contradicts Bassett (1959) by noting that most of the pyroxene crystals do not show this preferred orientation. The largest grains of diopside occur nearest to the contact with the biotitite. Fluorapatite is the most common accessory mineral and occurs as interstitial euhedral crystals and as small crystals within the diopside crystals (Boettcher, 1966a). The biotite pyroxenite and biotitite appear to be comagmatic (Boettcher, 1967). Several dikes of magnetite pyroxenite, have intruded into the biotite pyroxenite indicating a discontinuity in the intrusion of the ultramafic portion of the complex.



**Magnetite pyroxenite:** The magnetite pyroxenite has a uniform grain size (0.7-3 mm) and is composed of diopside, magnetite, and apatite with andradite, titanite, and biotite or vermiculite as accessory minerals. It constitutes approximately 40% of the intrusion (Boettcher, 1966a). The orientation of the magnetite pyroxenite relative to the two inner units is like that of a ring dike (Figure 5). The magnetite pyroxenite completely surrounds the inner units and the contact dips slightly outward from the center of the complex in all directions (Boettcher, 1966a). Diopside and apatite crystals are aligned and dip out from the center at varying angles. The magnetite pyroxenite also forms numerous small dikes that crosscut the biotite pyroxenite. The emplacement of the magnetite pyroxenite is thought to have occurred as an intrusion into a zone of weakness that formed between the Wallace Formation and the biotite pyroxenite (Boettcher 1967). The diopside in both of the pyroxenites is aluminum-deficient (Boettcher, 1967) as a result of the early fractionation of the biotite.

The remainder of the complex (approximately 35%) is composed of various alkaline rocks: syenite, nepheline syenite, trachyte, phonolite, alkaline pegmatite, and alkaline granites. The largest alkaline unit is an irregularly shaped body of variably altered syenite located in the southwest portion of the complex (Figure 5) and transects the earlier ultramafic units. This syenite has been altered and is observed in the replacement of nepheline by muscovite (Boettcher, 1966a). Syenite also occurs as dikes of varying width and is probably genetically related to the alkaline pegmatite dikes (Boettcher, 1966a). These dikes crosscut all of the ultramafic units. The smaller syenite dikes exhibit some compositional and textural variability that could be attributed to multiple intrusions of syenite magma (Larsen and Pardee, 1929). Intrusion of these dikes into the pyroxenite units caused significant wall rock alteration, resulting in the amphibolitization of pyroxene minerals. However, where these dikes occur in the biotite, little alteration of the biotite is observed. Dikes of trachyte, phonolite, and alkaline granite crosscut both these syenite and alkaline pegmatite dikes. The trachyte and phonolite dikes are interesting in that no wall rock alteration resulted from their intrusion. This feature suggested to Boettcher that these dikes penetrated near to the surface.

## MINERALOGY

Two major processes have significantly influenced the mineralogy of the RCC: magmatic differentiation and hydrothermal alteration. The biotite and the biotite pyroxenite are believed to have been the first units to crystallize from the original ultramafic magma (Boettcher, 1967). The early crystallization of large amounts of biotite preferentially differentiated aluminum from the melt. This early separation of biotite from the melt was facilitated by a high  $pH_2O$  (Boettcher, 1967). Boettcher concluded that the biotite, biotite pyroxenite, and magnetite pyroxenite are comagmatic. Later, syenite, trachyte, phonolite, and pegmatites intruded the previous units from a much more felsic magma and resulted in the alteration of diopside to amphiboles and biotite to vermiculite and hydrobiotite (Boettcher, 1967). The RCC still contains a large reserve of mineable vermiculite; however, the health effects associated with the amphibole-asbestos minerals in the pyroxenite units makes mining and milling of the vermiculite from this deposit a health hazard.

**Biotite, vermiculite, and hydrobiotite:** The biotite unit is almost entirely composed of biotite, whereas biotite comprises roughly 40% of the unaltered biotite pyroxenite and slightly less of the magnetite pyroxenite. Weathering of biotite in the biotite pyroxenite resulted in the formation of the vermiculite. Bassett (1959) and Boettcher (1966b) explored the chemical conditions necessary for the conversion of biotite to vermiculite. The hydrobiotite and amphibole are the product of higher temperature hydrothermal processes (Boettcher, 1966b).

The vermiculite of the RCC was shown by Boettcher (1966b) to have an upper stability limit of 350 °C. The chemistry of vermiculite indicates it was the result of leaching of biotite by groundwater. A lower content of alkali metals and higher amount of  $\text{Fe}^{3+}$  than that of biotite indicates a low-temperature leaching process altered the biotite to vermiculite. The hydrobiotite was shown in the same study to have an upper stability limit of as high as 480 °C. The hydrobiotite has a 1:1 stacking sequence of vermiculite and biotite that is not inherited from the biotite. This, along with the lack of a direct chemical relationship between hydrobiotite and biotite, indicates a much higher temperature hydrothermal alteration process. Bassett (1959) mentioned that miners used subtle color differences as an *ad hoc* method to distinguish areas in the mine richer in vermiculite than biotite or hydrobiotite; the biotite is black and durable, while the vermiculite is golden brown and friable.

**Pyroxenes:** The pyroxenes in the pyroxenite units are predominantly light green, non-pleochroic diopside (Boettcher, 1966a). Pyroxene accounts for over half of the minerals in the pyroxenite units. In hand sample, the diopside has perfect (100) parting and is emerald green in the biotite pyroxenite and darker green in the magnetite pyroxenite (Boettcher 1967a). The iron content of the diopside is elevated in later crystallizing units and especially when diopside is found in association with magnetite. The RCC also contains aegirine that has been examined by Goranson (1927) and Pardee and Larsen (1929). The aegirine is of interest because of its increased vanadium content. It occurs as black acicular crystals up to 2.5 cm in length that project from the walls of veins or as radiating nodules embedded in other minerals of the pegmatites occurring within the pyroxenites and biotite.

**Amphiboles:** Amphibolitization of the pyroxenes in the biotite pyroxenite produced nearly all of the amphibole in these rocks. Identifying the various amphibole species requires detailed chemical analysis (Leake et al., 1997). Until recently, there has been some confusion as to the classification of the asbestos minerals at Libby. Pardee and Larsen (1929) named the amphibole-asbestos minerals tremolite but stated there were "considerable" amounts of Na and Fe in their samples. The EPA and its contractors misidentified these minerals as tremolite (USEPA, 2000). The TEM-EDS data presented in the EPA study (USEPA, 2000) of vermiculite garden products shows that the samples from Libby vermiculite contain significant amounts of Na and K. This would mean these amphibole minerals could not possibly be tremolite. However, the incorrect name tremolite or actinolite persists in EPA literature and in the popular press. The amphiboles in the RCC have been called tremolite-actinolite (Larsen and Pardee, 1929), richterite (Larsen 1942), tremolite-actinolite (Bassett 1959), tremolite (Boettcher, 1963), richterite

(soda tremolite) (Deer et al., 1963), and winchite (Wylie and Verkouteren, 2000, Gunter et al., 2003). With the exception of Larsen (1942), Wylie and Verkouteren (2000), and Gunter et al. (2003), no previous worker had performed a chemical analysis of the amphibole mineral to correctly classify it. Meeker et al. (20003) performed chemical analysis of 30 samples they collected from various locations at the former mine site, and found approximately 70% of the amphiboles to be winchite, 20% richterite, 8% tremolite, and 2% magnesiorichterite.

Since the current OSHA and EPA regulations do not regulate all amphibole-asbestos minerals, it is crucial to understand the precise definition of the mineralogy of any asbestos containing material. The health effects associated with exposure to the amphibole-asbestos from this location are well documented (discussed below). This would suggest that current regulations regarding amphibole asbestos should be revised to include all amphibole-asbestos minerals, or at least winchite and richterite. Regardless of the mineral species or regulations, it is clear that the amphibole-asbestos mineral at Libby should be regulated in order to prevent unnecessary risk to public health.

## **HEALTH EFFECTS**

**General health effects of inhaled mineral dust:** It is generally understood that inhalation of mineral dusts will cause specific lung diseases to develop. There are numerous reviews on the health effects of inhaled mineral dusts. For instance, Reviews in Mineralogy Vol. 28 (Guthrie and Mossman, 1993) is a comprehensive presentation of mineralogical and medical topics related to how inhaled minerals affect human health, and the Canadian Mineralogist Special Publication #5 (Nolan et al., 2001) outlines the health effects associated with environmental exposure to chrysotile asbestos, with some discussion of amphibole-asbestos. Three diseases are associated with occupational exposure to asbestos: asbestosis, mesothelioma, and lung cancer.

Asbestosis is a type of pneumoconiosis that results from inhalation of large quantities of asbestos. Pneumoconiosis is a general term used to describe a disease associated with inhalation of large amounts of a specific type of dust into the lungs, and is a fibrotic lung disease where the alveoli are destroyed by the minerals. This hinders the lung's ability to exchange oxygen and carbon dioxide; as a result of decreased lung function, the heart is forced to pump faster, and a person with asbestosis usually dies from heart failure. Silicosis and anthracosis (black lung) are two types of pneumoconiosis associated with inhalation of quartz dust and coal dust, respectively (Gunter, 1999). In 1999, 1259 people in the United States died as a result of asbestosis (Centers for Disease Control (CDC), 2001).

Mesothelioma is a disease of the lining of the lung, the pleura, usually in the form of plaques. Plaques are not necessarily harmful; however, it is unclear if there is a connection between pleural plaques and malignant mesothelioma, which is usually fatal. It is not known why inhaled asbestos minerals cause reactions to occur in the pleura. Mesothelioma has a very long latency period, so it is difficult to diagnose and treat in early stages. This long latency period complicates the process of determining how much

asbestos an individual was exposed to prior to developing the disease. In 1999, 2502 people in the United States died as a result of mesothelioma (CDC, 2001).

Lung cancer is the third major disease associated with asbestos exposure. In 1998, 154,561 people died as a result of lung cancer in the United States (American Lung Association (ALA), 2001). However, most lung cancer cases are associated with cigarette smoking. Therefore, it becomes difficult to separate lung cancers that may not have been caused by asbestos from those caused by other carcinogens.

The amount of a certain mineral a person inhales is an important factor to consider. A fundamental concept of the study of mineral-induced lung diseases is that the dose makes the poison (Gunter, 1994). Mesothelioma and lung cancer may develop after inhalation of moderate or small quantities of asbestos dust. The relationship between dose and disease is complicated and has yet to be accurately defined.

It also appears that the type of asbestos an individual inhales is an important factor in determining what lung disease may develop. Epidemiological studies indicate variability in the potential for different asbestos minerals to cause diseases in humans. Amphibole asbestos minerals pose a much greater threat than other asbestos minerals (Kane, 1993). Tremolite has been described as the most dangerous of the amphibole-asbestos minerals (Case, 1991), though this was, ironically, based on the definitive epidemiological studies of workers exposed to "tremolite-asbestos" from the Libby vermiculite mine.

Regardless of the species of amphibole-asbestos, it appears that amphibole-asbestos minerals pose a greater risk than chrysotile asbestos (Gunter, 1994). This is for a variety of reasons, including the fact that amphiboles are insoluble when exposed to the chemical conditions in the lung. Many case and *in vitro* studies have shown that when dusts containing significant amounts of chrysotile and minor amounts of amphibole-asbestos are inhaled, lung burdens at the time of death contain many more amphibole-asbestos fibers than chrysotile fibers (Davis et al., 1991). It has also been shown that the carcinogenic potential of amphibole-asbestos is significantly higher than that of other minerals (Weill et al., 1990). It is important to note that amphibole-asbestos has not been extensively mined or used in manufactured products and exposure is usually through background environmental dust or as a contaminant in some other mined or quarried material (Ross, 1981). However, the probability that background environmental exposure to amphibole-asbestos results in asbestos-related lung disease, mesothelioma in particular, is very small (Browne and Wagner, 2001).

The health effects associated with amphibole minerals may also be dependent on the morphology of the inhaled particles. Asbestos fibers appear to pose a greater risk than cleavage fragments. There also appears to be a correlation between increased potential to cause disease and increased aspect ratio. The result of this is that amphibole cleavage fragments (which have a low aspect ratio) have not been shown to cause disease in humans and are therefore not regulated, whereas asbestos fibers (which have a high aspect ratio) are known to cause disease and are regulated (Dorling and Zussman, 1987). It has also been noted that there may be a correlation between particles that exhibit (110)

cleavage and those that exhibit (100) twinning and effects on human health (Zoltai 1981), and there may also be a correlation between increased disease potential and other dimensional ratios that have yet to be studied (Davis et al., 1991). Gunter et al. (2003) showed that approximately one half of amphiboles at Libby exhibit asbestiform morphology based on counting of several hundred particles with a polarizing light microscope.

**Health effects observed in Libby:** Health effects observed in Libby workers are typical of other groups exposed to amphibole-asbestos. It is important to note that no adverse health effects have been observed from exposure to vermiculite alone (Ross et al., 1993). Lockey et al. (1984) examined a group of vermiculite workers who were exposed to "tremolite-asbestos" in the vermiculite ore, and determined that occupational exposure to asbestos-contaminated vermiculite could cause pleural changes. Other epidemiological studies showed substantially increased risks of lung cancer, malignant mesothelioma, and pleural changes (McDonald et al. 1988; Amandus 1987b).

The studies of McDonald et al. (1986a, 1986b, 1988), Amandus and Wheeler (1987), and Amandus et al. (1987a, 1987b) were performed in parallel and studied the health of men who were involved with mining and processing the vermiculite from the RCC. W.R. Grace funded the McDonald et al. (1986a, 1986b, 1988) studies, and the National Institute for Occupational Safety and Health (NIOSH) funded the Amandus and Wheeler (1987) and Amandus et al. (1987a, 1987b) studies. Both studies estimated the amounts of airborne asbestos workers were exposed to and calculated standard mortality ratios (SMR) for various diseases. These studies provide the definitive evidence that the amphibole-asbestos from the RCC is harmful to humans.

McDonald et al. (1986a, 1986b, 1988) showed that there was a significantly higher incidence of lung cancer and nonmalignant respiratory disease in workers of the Libby vermiculite mine. The study examined the exposure levels and health histories of 406 men employed for at least one year before 1963. It was determined that the SMR for lung cancer (SMR = 2.45) and nonmalignant respiratory disease (SMR = 2.55) were significantly higher for this cohort than for the white male population of the United States (McDonald et al., 1986a). The exposure levels were variable and dependent on workstation activity (Table 3) (McDonald et al., 1986b). It was shown that after W.R. Grace acquired the mine, dust levels decreased significantly. It was also shown that for each fiber-year of exposure there was a 1% increase in the probability of a worker developing lung cancer (McDonald et al., 1988).

Amandus and Wheeler (1987) and Amandus et al. (1987a, 1987b) replicated the studies of McDonald et al. (1986a, 1986b, 1988). These studies examined the exposure levels and health histories of 575 men who had been hired before 1970 and were employed at least one year. Exposure estimates (Amandus et al., 1987a) were determined using previous measurements and workstation activities. Amandus et al. (1987a) estimated the exposure rates for workers at the Libby vermiculite operations and determined that from the onset of mining to the mid 1980's there was a significant decrease in the levels of airborne asbestos (Table 3). These data were used to determine individual cumulative

fiber exposure (fiber-year). The estimates show that, in general, exposure was highly variable depending on a worker's workstation activity. SMR for lung cancer (SMR = 2.44) and nonmalignant respiratory diseases (SMR = 2.42) were found to be significantly higher than that of the general white male population in the United States. The increase in the risk of developing lung cancer was determined to be 0.6% for each fiber-year of exposure (Amandus and Wheeler, 1987). These two studies show that the asbestos minerals present in the Libby vermiculite ore posed a significant health risk to workers who were exposed at high levels.

Both McDonald et al. (1986a) and Amandus et al. (1987a) showed that workers employed before 1970 were exposed to significantly higher levels of amphibole-asbestos than those employed later. Table 3 gives estimated amphibole-asbestos dust levels at various workstations during the life of the mine. Dust levels were not measured in all years, so dust levels were assumed to remain constant until the next measurement was made. The data show several significant changes in the amounts of dust the workers at Libby were exposed to. Dust levels were extremely high in the dry mill before W.R. Grace acquired the operation in 1963, and dust levels were reduced by approximately 75% by 1965. With the elimination of the dry mill in 1974, the largest source of airborne amphibole-asbestos fibers was removed, and with the introduction of federal regulations in 1972 (Table 2), the fiber exposure for workers was reduced further. The McDonald et al. (1986a) estimates are consistently lower than those of Amandus et al. (1987a), but both show the consistent trend of decreasing fiber exposure with time.

Preliminary results of a recent Agency for Toxic Substances and Disease Registry study (ATSDR, 2001) of 5590 Libby residents reveal that 18% of the population have pleural abnormalities; 2% had no direct exposure to asbestos, and 5% of those who had no direct exposure (0.1% of the study group) have lung abnormalities consistent with asbestos exposure. This may mean that the asbestos at Libby is hazardous even at very low exposure levels. However, there is very little information about how much asbestos residents of Libby were actually exposed to. The major concern is that environmental exposure to the amphibole-asbestos from Libby is harmful.

## SUMMARY

The RCC alkaline-ultramafic igneous intrusion was mined for 67 years for its rich deposit of vermiculite, which has numerous industrial applications. It still contains significant amounts of vermiculite ore. However, the geologic processes that created the vermiculite also created amphibole-asbestos. As pressure from the regulatory agencies and residents of Libby to remove asbestos contamination from the vermiculite mining and milling operations in Libby and elsewhere around the U.S. continues, more information about exactly what species of amphibole minerals will be required. The classification of the amphibole-asbestos in vermiculite products that originated from the Libby mine has been clouded in confusion. For the past two years, the EPA and the media have continued to call these amphibole minerals tremolite when indeed they are not. Correct classification of these harmful minerals will require a change in the regulations to protect human health. Ironically and interestingly, much of the health risks of tremolite have been based

on the misconception that the amphibole and amphibole-asbestos found at Libby was tremolite.

Since November of 1999, the EPA has been actively involved in abatement of asbestos contamination resulting from the vermiculite mining and milling operations at Libby. The main focus of the EPA's cleanup effort has been on the export plant at the mouth of Rainy Creek, but several other sites in Libby, including the Libby High School, Burlington Northern and Santa Fe Railway yard, and multiple residential areas are being considered for asbestos cleanup projects. Currently, the EPA is considering placing these areas in Libby on its National Priority List or listing the area as a Superfund site. Tens of millions of dollars have already been spent cleaning up the former export plant and several other locations in Libby where vermiculite was used for various purposes. In order to clean up all asbestos contamination in Libby, it will take between \$40 and \$60 million over 3 years (Drumheller, 2001). A final decision by the EPA as to how it will deal with asbestos contamination at Libby will be made in the near future. It will also be necessary to decide how to handle the vermiculite insulation that was used in millions of homes across the United States, and to examine the levels of asbestos contamination that occurred at the numerous vermiculite expansion facilities that were operated by Zonolite and W.R. Grace.

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#### **REFERENCES CITED**

- Amandus, H.E. and Wheeler, R., 1987, The morbidity and mortality of vermiculite miners and millers exposed to tremolite-actinolite: Part II. Mortality: *American Journal of Industrial Medicine*, v. 11, p. 15-26.
- Amandus, H.E., Wheeler, R., Jankovic, J., and Tucker, J., 1987a, The morbidity and mortality of vermiculite miners and millers exposed to tremolite-actinolite: Part I. Exposure estimates: *American Journal of Industrial Medicine*, v. 11, p. 1-14.
- Amandus, H.E., Althouse, R., Morgan, W.K.C., Sargent, E.N., and Jones, R., 1987b, The morbidity and mortality of vermiculite miners and millers exposed to tremolite-actinolite: Part III. Radiographic findings: *American Journal of Industrial Medicine*, v. 11, p. 27-37.
- American Lung Association, 2001, Trends in lung cancer morbidity and mortality, p. 22. American Lung Association, New York.
- Agency for Toxic Substances and Disease Registry, 2001, Year 2000 medical testing of individuals potentially exposed to asbestiform minerals associated with vermiculite in Libby, Montana, 30p: U.S. Department of Health and Human Services, Atlanta, Georgia.
- Bassett, W.A., 1959, The origin of the vermiculite deposit at Libby, Montana: *American Mineralogist*, v. 44, p. 282-299.
- Boettcher, A.L., 1963, Geology and petrology of the Rainy Creek intrusive near Libby, Montana. M.S. thesis, 70p.: Pennsylvania State University, University Park.

- Boettcher, A.L., 1966a, The Rainy Creek igneous complex near Libby, Montana. Ph.D. dissertation, 155p.: Pennsylvania State University, University Park.
- Boettcher, A.L., 1966b, Vermiculite, hydrobiotite, and biotite in the Rainy Creek igneous complex near Libby, Montana: *Clay Minerals*, v. 6, p. 283-296.
- Boettcher, A.L., 1967, The Rainy Creek alkaline-utramafic ingeous complex near Libby, Montana. I: Ultramafic rocks and fenite: *Journal of Geology*, v. 75, p. 526-553.
- Browne, K. and Wagner, J.C., 2001, Environmental exposure to amphibole-asbestos and mesothelioma. In Nolan, R.P., Langer, A.M., Ross, M., Wicks, F.J., Martin, R.F., Eds. (2001) *The health effects of chrysotile asbestos: contribution of science to risk-management decisions*, 304p.: Special Publication #5, Mineralogical Association of Canada, Ottawa.
- Case, B.W., 1991, Health effects of tremolite. In P.J. Landrigan, H. Kazemi, *The third wave of asbestos disease: Exposure to asbestos in place*, *Annals of the New York Academy of Sciences*, v. 643, p. 491-504.
- Centers for Disease Control, 2001, *Health, United States, 2001*, 460 p.: Centers for Disease Control, Atlanta, Georgia.
- Davis, J.M.G., Addison, J., McIntosh, C., Miller, B.G., and Niven, K., 1991, Variations in the carcinogenicity of tremolite dust samples of differing morphology. In P.J. Landrigan, H. Kazemi, *The third wave of asbestos disease: Exposure to asbestos in place*, *Annals of the New York Academy of Sciences*, v. 643, p. 473-490.
- Deer, W.A., Howie, R. A., and Zussman, J., 1963, *Rock-forming minerals*; vol. 2, Chain silicates, 379 p.: Longmans, London.
- Dorling, M. and Zussman, J., 1987, Characteristics of asbestiform and non-asbestiform calcic amphiboles: *Lithos*, v. 20, p. 469-489.
- Drumheller, S., 2001, Libby asks state to speed superfund status: *The Spokesman Review*, Friday, November 23.
- Goranson, R.W., 1927, Contributions from the Department of Mineralogy and Petrography, Harvard University: Aegirite from Libby, Montana: *American Mineralogist*, v. 12, p. 37-39.
- Gunter, M.E., 1994, Asbestos as a metaphor for teaching risk perception: *Journal of Geological Education*, v. 42, p. 17-24.
- Gunter, M.E., 1999, Quartz – the most abundant mineral in the earth's crust and a human carcinogen: *Journal of Geoscience Education*, v. 86, p. 341-349.
- Gunter, M.E., Brown, B.R., Bandli, B.R., Dyar, M.D., Foit, F.F., Jr., and Cornelius, S., 2003, Crystal chemistry, crystal structure, and morphology of amphibole and amphibole-asbestos from Libby, Montana U.S.A.: *American Mineralogist* (submitted).
- Guthrie, G.D., Jr. and Mossman, B.T., 1993, Health effects of mineral dusts, 584 p.: *Reviews in Mineralogy*, Mineralogical Society of America, Washington, D.C.
- Kane, A.B., 1993, Epidemiology and pathology of asbestos-related diseases. In G.D. Guthrie Jr., and B.T. Mossman, Eds., *Health Effects of Mineral Dusts*, p. 347-358: *Reviews in Mineralogy*, Mineralogical Society of America, Washington, D.C.
- Kriegel, W.W., 1940, Summary of occurrence, properties, and uses of vermiculite at Libby, Montana: *American Ceramic Society Bulletin*, v. 19, p. 94-97.
- Lang, H.M., 1998, A case study approach to teaching environmental mineralogy: *Journal of Geoscience Education*, v. 46, p. 354-363.



- Larsen, E.S., 1942, Alkalic rocks of Iron Hill, Gunnison County, Colorado: U.S. Geological Survey Professional Paper, 197A.
- Larsen, E.S. and Pardee, J.T., 1929, The stock of alkaline rocks near Libby, Montana: *Journal of Geology*, v. 37, p. 97-112.
- Leake, B.E., Woolley, A.R., Arps, C.E.S., Birch, W.D., Gilbert, M.C., Grice, J.D., Hawthorne, F.C., Kato, A., Kisch, H.J., Krivovichev, V.G., Linthout, K., Laird, J., Mandarino, J.A., Maresch, W.V., Nickel, E.H., Rock, N.M.S., Schumacher, J.C., Smith, D.C., Stephenson, N.C.N., Ungaretti, L., Whittaker, E.J.W., and Youzhi, G., 1997, Nomenclature of the amphiboles: Report of the subcommittee on amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names: *Canadian Mineralogist*, v. 35, p. 219-246.
- Lockey, J.E., Brooks, S.M., Arabic, A.M., Khoury, P.R., McKay, R.T., Carson, A., Morrison, J.A., Woit, J.F., and Spitz, H.B., 1984, Pulmonary changes after exposure to vermiculite contaminated with fibrous tremolite: *American Review of Respiratory Diseases*, v. 129, p. 952-958.
- Meeker, G.P., Bern, A.M., Brownfield, S.J., Sutley, S.J., Hoefen, T.M., Vance, J.S., and Lowers, H.A., 2003, The composition and morphology of prismatic, fibrous and asbestiform amphibole from the Rainy Creek District, Libby, Montana: *American Mineralogist* (submitted).
- McDonald, J.C., McDonald, A.D., Armstrong, B., and Sebastien, P., 1986a, Cohort study of the mortality of vermiculite miners exposed to tremolite: *British Journal of Industrial Medicine*, v. 43, p. 436-444.
- McDonald, J.C., Sebastien, P., and Armstrong, B., 1986b, Radiological survey of past and present vermiculite miners exposed to tremolite: *British Journal of Industrial Medicine*, v. 43, p. 445-449.
- McDonald, J.C., McDonald, A.D., Sebastien, P., and Moy, K., 1988, Health of vermiculite miners exposed to trace amounts of fibrous tremolite: *British Journal of Industrial Medicine*, v. 45, p. 630-634.
- Montana Department of Environmental Quality, 2000, W.R. Grace file review summary, CVID# 3726: <http://deq.state.mt.us/libby/wrgracetimeline3113099.htm>.
- Nolan, R.P., Langer, A.M., Oechsle, G.W., Addison, J., and Colflesh, D.E., 1991, Association of tremolite habit with biological potential: Preliminary report. In R.C. Brow, J.A. Hoskins, N.F. Johnson, Eds., *Mechanisms in fibre carcinogenesis*, p. 231-251.
- Nolan, R.P., Langer, A.M., Ross, M., Wicks, F.J., Martin, R.F., 2001, The health effects of chrysotile asbestos: contribution of science to risk-management decisions, 304p.: Special Publication #5, Mineralogical Association of Canada, Ottawa.
- Pardee, J.T. and Larsen, E.S., 1929, Deposits of vermiculite and other minerals in the Rainy Creek District, near Libby, Montana: U.S.G.S., Bulletin v. 805, p. 17-28.
- Ross, M., 1981, Geologic occurrences and health hazards of amphibole and serpentine asbestos: In D.R. Veblen Ed., *Amphiboles and other Hydrous Pyriboles-mineralogy*, p. 279-324. Reviews in Mineralogy, Mineralogical Society of America, Washington, D.C.
- Ross, M., Nolan, R.P., Langer, A.M., and Cooper, C.W., 1993, Health effects of mineral dusts other than asbestos: In G.D. Guthrie Jr., and B.T. Mossman, Eds., *Health*

- Effects of Mineral Dusts, p. 361-409. Reviews in Mineralogy, Mineralogical Society of America, Washington, D.C.
- United States Environmental Protection Agency, 2000, Sampling and analysis of consumer garden products that contain vermiculite: Report 2001-S-7, United States Environmental Protection Agency, Washington D.C.
- United States Environmental Protection Agency, 2001, EPA's actions concerning asbestos-contaminated vermiculite in Libby, Montana: EPA 744-R-00-010, United States Environmental Protection Agency, Washington D.C.
- Weill, H., Abraham, J.L., Balmes, J.R., Case, B., Chrug, A., Hughes, J., Schenker, M., and Sebastien, P., 1990, Health effects of tremolite. American Review of Respiratory Diseases, 142, 1453-1458.
- W.R. Grace, 2000, Libby asbestos time line:  
[http://www.grace.com/mediakit/libby\\_asbestos\\_timeline.html?image=grace%20in%20the%20news](http://www.grace.com/mediakit/libby_asbestos_timeline.html?image=grace%20in%20the%20news).
- Wylie, A.G. and Verkouteren, J.R., 2000, Amphibole asbestos from Libby, Montana: Aspects of nomenclature: American Mineralogist, v. 85, p. 1540-1542.
- Zoltai, T., 1981, Amphibole asbestos mineralogy: In D.R. Veblen Ed., Amphiboles and other hydrous pyriboles - Mineralogy, p. 237-279. Reviews in Mineralogy, Mineralogical Society of America, Washington, D.C.

### Tables

Table 1. Timeline of events significant to vermiculite mining operations at Libby Montana. (Note: Data obtained from Montana Department of Environmental Quality (2000) and W.R. Grace (2000).)

Year	Event
1919	E.N. Alley observes exfoliation of vermiculite in roof of mine audit
1923	Commercial mining of vermiculite begins on Vermiculite Mountain by E.N. Alley
1939	E.N. Alley's Zonolite business becomes the Universal Zonolite Insulation Company
1944	First dust control equipment installed
1948	Universal Zonolite Insulation Company changes name to Zonolite Company
1954	First "wet" mill installed at Libby mine
1956	State of Montana conducts a study to examine the working conditions at the Zonolite Company facilities in Libby
1959	State of Montana conducts a follow-up study of the 1956 study and finds dust levels are lower, but asbestos content of dust collected in the vermiculite mill is determined to be 27%
1963	W.R. Grace purchases Zonolite Company
1964	W.R. Grace begins X-ray testing of employees
1970	Occupational Safety and Health Act creates Occupational Health and Safety Administration (OSHA)
1972	First federal regulations limiting exposure of workers to asbestos are enacted by OSHA (5 fibers/cc)

- 1973 Clean Air Act enacted placing limits on amounts of asbestos industries can release into the environment
- 1974 "Dry" milling of vermiculite ore discontinued
- 1977 W.R. Grace initiates policy of not hiring individuals who smoke cigarettes
- 1977 Federal Mine Safety and Health Act enacted to create safer working environment for miners
- 1986 W.R. Grace receives permission to expand vermiculite mine to 1004 acres (this is the largest area the mine will cover)
- 1990 September: mining operations at Vermiculite Mountain end
- 1991 Reclamation at mine site begins
- 1994 W.R. Grace sells Vermiculite Mountain mine site to Kootenai Development Company
- 1997 Reclamation bond released on 900 acres of Vermiculite Mountain mine
- 1999 November, Seattle Post-Intelligencer publishes a series of articles about the high incidence of asbestos related lung disease among Libby, Montana residents
- 1999 November, EPA begins investigating asbestos contamination in and around Libby
- 2000 W.R. Grace initiates medical program to provide medical coverage for Libby residents and buys back Vermiculite Mountain mine site from Kootenai Development Company
- 2001 Agency for Toxic Substances and Disease Control begins health screening program for current and past Libby residents

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Table 2. Regulations for occupational exposure and environmental releases of mineral dust.

Year	Regulation	Exposure limit
1946	ACGIH	5 mppcf*
1968	ACGIH	12 fibers/cc
1972	OSHA	5 fibers/cc 8hr. TWA**
1973	Clean Air Act	Sets no specific release levels, but mandates practices for handling asbestos containing materials
1976	OSHA	2 fibers/cc 8hr. TWA
1977	Mine Act	2 fibers/cc 8hr. TWA
1986	OSHA	0.2 fibers/cc 8hr. TWA
1992	OSHA	0.1 fibers/cc 8hr. TWA, and deregulates amphibole cleavage fragments

\* mppcf = millions of particles per cubic foot

\*\* TWA = time weighted average

Note: 1946 and 1968: recommendations made by the American Conference of Governmental Industrial Hygienists. The exposure levels recommended at these times were not enforced by any regulatory agency.

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Table 3. Fiber exposure estimates in fibers/ml (1: McDonald et al. 1986a, 2: Amandus et al. 1987a).

Workstation		Year						
		pre-1950	1955	1960	1965	1970	1975	1980
Dry mill	1	101.5	101.5	101.5	22.1	22.1	--	--
	2	168.4	168.4	168.4	33.2	33.2	--	--
Wet mill	1	--	--	--	--	3.9	1.5	0.8
	2	--	--	--	--	3.2	2.0	0.8
Drilling	1	--	12.5	12.5	12.5	5.2	5.2	0.8
	2	23.0	23.0	23.0	23.0	9.2	0.6	0.6
Concentrate loading	1	24.0	15.0	15.0	9.0	9.0	4.8	0.2
	2	82.5	27.7	10.7	10.7	3.2	0.2	0.2
Skip area	1	--	68.8	68.8	15.0	15.0	2.0	0.6
	2	88.3	88.3	88.3	17.4	17.4	0.6	0.6
River dock	1	--	--	12.0	12.0	12.0	12.0	0.7
	2	116.9	42.5	17.0	17.0	17.0	5.1	0.5

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### Figure Captions, Figures on next two pages

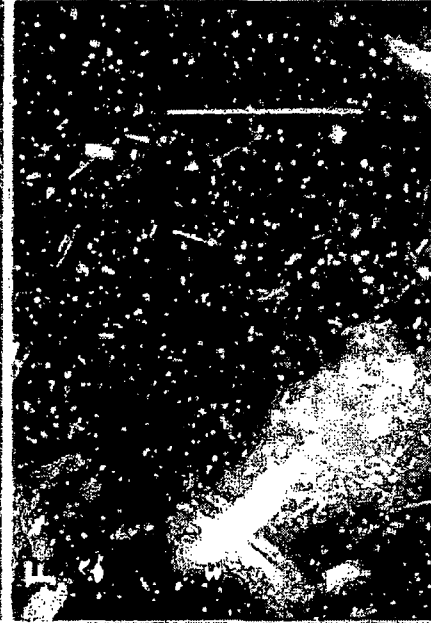
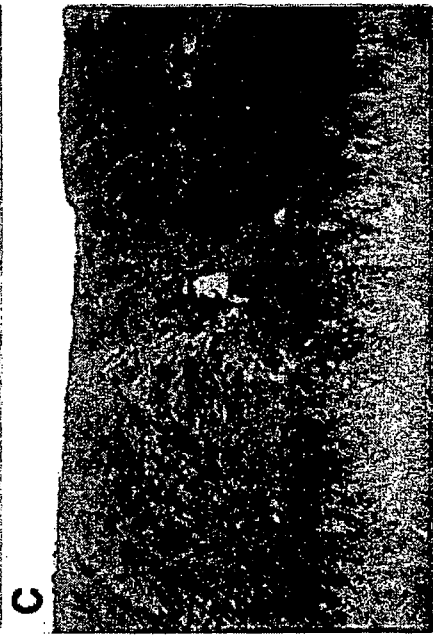
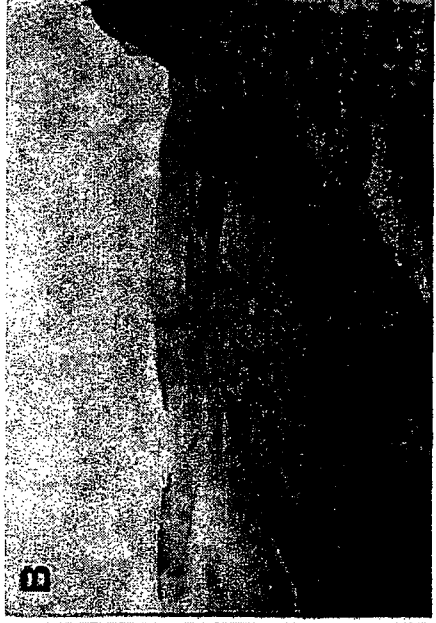
Figure 1: A. View from Rainy Creek Road east toward Vermiculite Mountain. B. View from vermiculite mountain toward Libby with mine benches visible in the middle of the photo (benches approx. 7 m. high). C. View of mine bench showing amphibole-asbestos vein (MEG for scale). D. Photograph of biotite pyroxenite. Light-colored grains are amphibole, medium-gray grains are pyroxenes, and dark-gray grains are biotite/vermiculite (knife for scale). E. Photograph of boulder composed entirely of amphibole (knife for scale). F. Photomicrograph of material from Vermiculite Mountain mine. High aspect ratio amphibole fragment (inclined extinction) visible on right side and large amphibole-asbestos fiber bundle (parallel extinction) visible in lower left corner.

Figure 2: Aerial photograph of former vermiculite mine. Photo is approximately 3 km across.

Figure 3: Map of Libby, Montana and former vermiculite mine (adapted from USEPA, 2001).

Figure 4: Photograph showing raw (unexpanded) vermiculite on left, partly expanded vermiculite at center, and completely expanded (exfoliated) vermiculite on right (cigarette lighter for scale).

Figure 5: Geologic map of RCC (adapted from Boettcher, 1966a).



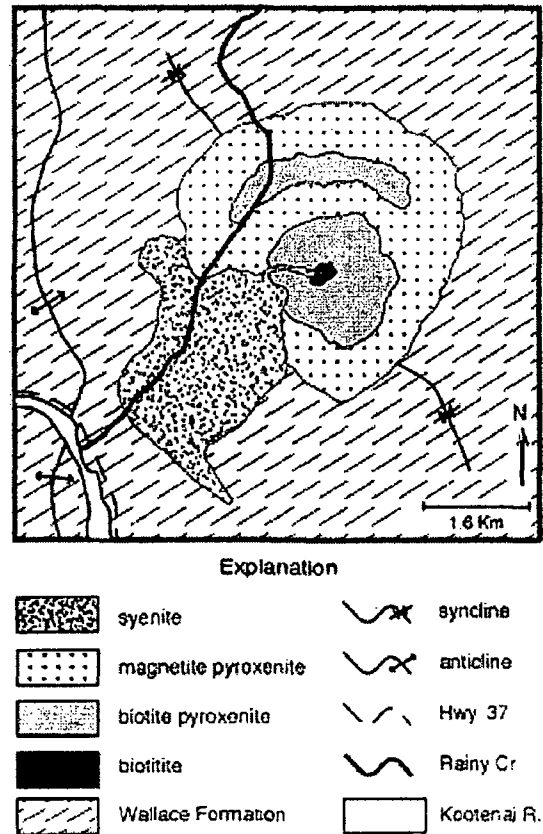
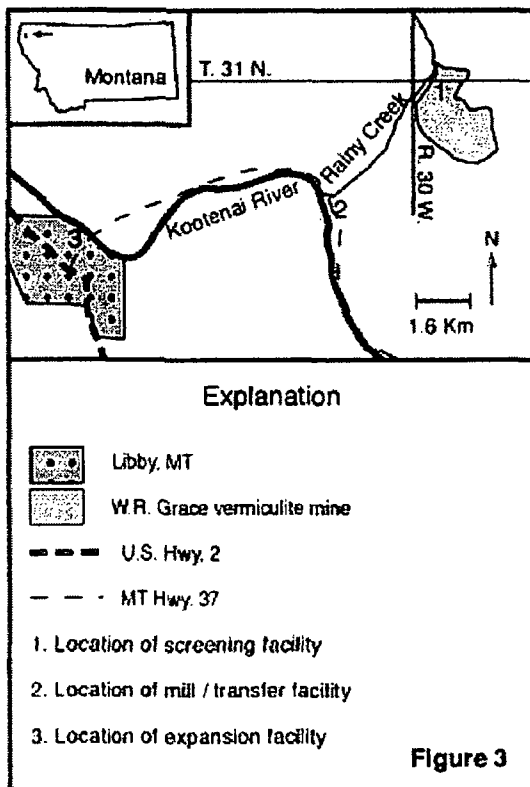
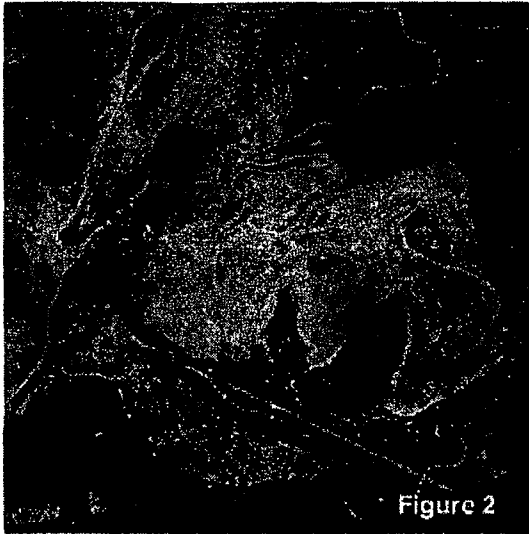


Figure 5

# HEALTH EFFECTS OF MINERAL DUSTS

George D. Guthrie, Jr.,  
Brooke T. Mossman, *Editors*

Proceedings of a short course endorsed by  
THE AMERICAN COLLEGE OF CHEST PHYSICIANS  
and THE U. S. GEOLOGICAL SURVEY

**COVER:** Scanning electron micrograph of ferruginous bodies extracted from autopsied human lung. The individual was exposed primarily to chrysotile. The particles consist of asbestos fibers coated by an iron-rich material believed to derive from proteins such as ferritin or hemosiderin. The ferruginous bodies are generally about 5 to 30- $\mu$ m long; the species of asbestos is not known. Photo courtesy of Lesley S. Smith and Anne F. Sorling (Department of Pathology, Fox Chase Cancer Center, Philadelphia, Pennsylvania).



MINERALOGICAL SOCIETY OF AMERICA  
WASHINGTON, D.C.



- Thomassen, D.G., Kaighn, M.E. and Saffiotti, U. (1986) Clonal proliferation of rat tracheal epithelial cells in serum-free medium and their responses to hormones, growth factors and carcinogens. *Carcinogenesis* 7, 2033-2039.
- Vallyathan, V., Shi, X., Dalal, N.S., Irr, W. and Castranova, V. (1988) Generation of free radicals from freshly fractured silica dust. *Amer. Rev. Resp. Dis.* 138, 1213-1219.
- Wagner M.M.F., Wagner J.C., Davies R. and Griffiths D.M. (1980) Silica-induced malignant hystiocytic lymphoma: incidence linked with strain of rat and type of silica. *Brit. J. Cancer* 41, 908-917.
- Williams, A.O., Flanders, K.C. and Saffiotti, U. (1993) Immunohistochemical localization of transforming growth factor- $\beta$ 1 in rats with experimental silicosis, alveolar type II hyperplasia, and lung cancer. *Amer. J. Pathol.* 142, 1831-1840.

## CHAPTER 19

# REGULATORY APPROACHES TO REDUCE HUMAN HEALTH RISKS ASSOCIATED WITH EXPOSURES TO MINERAL FIBERS

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## INTRODUCTION

An important task for environmental protection is to identify, and subsequently to prevent the hazards to human health posed by toxic substances. Asbestos and related mineral fibers are one group of substances that have been identified as priority substances for risk reduction and pollution prevention. Because of the known health effects associated with past occupational exposures to elevated levels of asbestos, and because of the widespread use of asbestos in commerce, there has been considerable concern that exposures to asbestos may present a health hazard to workers and the general public. All major types of asbestos are associated with pulmonary fibrosis (asbestosis), lung cancer, mesotheliomas of the pleura and peritoneum in a dose-related manner.<sup>†</sup> Cancer at other sites (e.g., gastrointestinal cancer, laryngeal cancer) has also been shown to be associated with asbestos exposure, but the degree of excess risk and the strength of association are considerably less than for lung cancer and mesothelioma (IPCS, 1986; USEPA, 1986; ATSDR, 1990).

There is also a health concern for many other types of natural and synthetically made fibers whose commercial uses have been growing in recent years as replacement materials for asbestos-containing products. Yet, only limited information is available concerning their potential health effects and the exposure levels to workers, consumers, and the general public.

Studies conducted to date suggest that occupational exposures to rock wool and slag wool have produced an increased incidence of lung cancer in humans. Whether this increase is actually due to mineral wool exposure, to other contaminants, or to other factors remains to be determined (IARC, 1988; USEPA, 1988; HEI, 1991). In experimental studies, man-made mineral fibers and a variety of synthetic organic and inorganic fibers cause pulmonary fibrosis, lung cancer, and/or mesotheliomas in rats and hamsters under certain exposure conditions (IARC, 1988; USEPA, 1988; Vu and Dearfield, 1993). However, to date, only refractory ceramic fibers (RCF) have been shown conclusively to induce lung fibrosis, lung cancer and/or mesotheliomas in exposed animals by inhalation (IRIS, 1992; Vu, 1992; Vu, 1993).

<sup>†</sup> The relationship between chrysotile and mesothelioma is currently hotly debated (e.g., see Chapters 11 and 13).—Eds.

Erionite is the only natural fiber other than asbestos for which a high incidence of mesothelioma resulting from environmental exposures has been documented. Erionite has also been found to be extremely carcinogenic in rats following inhalation (IPCS, 1986; IARC, 1987; USEPA, 1988a). Erionite, however, is not known to be available in commerce at this time.

This chapter provides an overview of past and current regulatory activities relating to mineral fibers. Various approaches have been utilized by the federal agencies in the U.S. to reduce health risks associated with exposures to asbestos and other mineral fibers. These approaches are generally in the form of regulations, enforceable consent orders, negotiated voluntary actions, advisories, hazard communication, and guidance documents.

### MAJOR REGULATIONS AND GUIDELINES ON ASBESTOS

There are many sources of exposures to asbestos. In addition to exposures from natural sources (e.g., see Chapter 2), humans are exposed to asbestos fibers during activities such as mining, milling, manufacturing, use, demolition, and disposal. There can be exposure to asbestos from other sources including schools, public and private buildings that have asbestos-containing materials, ambient air and water, and drinking water. Regulations and guidelines have been established by the various regulatory authorities in the U.S. (1) to limit exposure to asbestos in the workplace; (2) to minimize emissions of asbestos into the atmosphere from activities involving the milling, manufacturing, and processing of asbestos, demolition and renovation of asbestos-containing buildings, and the handling and disposal of asbestos-containing waste materials; (3) to control asbestos-containing materials in schools and in buildings; (4) to limit the level of asbestos in ambient water and drinking water; and (5) to restrict or to prohibit the use of asbestos in certain products and applications.

#### Occupational exposure limits and work practices

Asbestos was the first group of substances for which a comprehensive standard was issued in 1972 by the Occupational Safety and Health Administration (OSHA) under section 6(b) of the Occupational Safety and Health Act (OSH Act). The OSH Act of 1970 established OSHA to provide working conditions that are safe for employees, and it empowers the agency to prescribe mandatory occupational safety and health standards "which most adequately assures, to the extent feasible, on the basis of best available evidence, that no employee will suffer material impairment of health or physical capacity even if such employee has regular exposure for the period of his working life."

The 1972 asbestos standard established a Permissible Exposure Limit (PEL) for asbestos of 2.0 fibers per cubic centimeter (or f/ml) as an 8-hour time-weighted average (TWA). The standard also prescribed methods of compliance, personal protective equipment, employee monitoring, medical surveillance, hazard communication to employees, housekeeping procedures, and record keeping (OSHA, 1972). The standard of 1972 was intended primarily to protect workers against asbestosis and thereby to provide some protection from asbestos-

associated cancer. In 1986, OSHA revised the asbestos standard based on the sufficient evidence that asbestos is a human carcinogen, and that the 1972 standard does not adequately protect workers from asbestos-related hazards. The 1986 asbestos standards reduced the PEL from 2.0 f/ml to 0.2 f/ml and updated other requirements. These standards, which remain in effect at present, apply to all industries including the construction and maritime industries and general industry (OSHA, 1986). As pointed out by OSHA, the current exposure limits do not represent "safe" levels of exposure, but are the lowest levels that industry can feasibly achieve using current control technologies.

Regulations to limit asbestos exposure during mining and milling activities have been issued by the Mine Safety and Health Administration (MSHA) under the Federal Mine Safety and Health Act (Mine Act). The Mine Act of 1977 established MSHA to control the hazards of exposure to potentially harmful substances generated by mining activity or used in the mining or milling process. The Mine Act requires that MSHA, in promulgating a standard, attain the highest degree of health and safety protection for the miner, with feasibility of engineering controls and cost of compliance as additional considerations. The current health standard for asbestos specifies an 8-hour TWA exposure limit of 2 f/ml and provisions for labeling, use of protective equipment, engineering controls, and monitoring miners' exposures (MSHA, 1977). Consistent with OSHA's asbestos standard, MSHA recently proposed to lower the asbestos exposure limit to 0.2 f/ml (MSHA, 1989).

Since OSHA's asbestos health standards only apply to worker exposures in the private sector, the Environmental Protection Agency (EPA) has used its legal authority under Title II of the Toxic Substances Control Act (TSCA) to issue a regulation known as EPA Asbestos Worker Protection Rule (USEPA, 1987a). This rule requires comprehensive work practices as provided under the OSHA asbestos standard to protect employees in the public sector (state and local government employees) who are engaged in asbestos abatement work. The EPA rule also contains a provision not included in the OSHA rule, i.e., notification to EPA generally 10 days before an asbestos abatement project is begun when public employees are doing the work.

#### Air emissions control and waste disposal

Emissions of asbestos to the ambient air are regulated under the Clean Air Act (CAA). EPA, under the CAA of 1971, is required to develop and to enforce regulations necessary to protect the general public from exposure to air pollutants that are known to be hazardous to human health. EPA designated asbestos as a hazardous air pollutant and issued a National Emission Standards for Hazardous Air Pollutant (NESHAP) rule for asbestos in 1973 under section 112 of the CAA. The Asbestos NESHAP has been amended several times; the last revision was promulgated in 1990 to enhance enforcement and to promote compliance (USEPA, 1990a).

The Asbestos NESHAP requires specific emission control requirements for the milling, manufacturing, and fabricating of asbestos, for activities associated

## Health standards for drinking water and effluent guidelines

Under the Safe Drinking Water Act of 1972 (SDWA), EPA is required to regulate drinking water contaminants which "may have an adverse effect on human health." Drinking water in the U.S. is known to be contaminated with asbestos fibers resulting from mining operation, geologic erosion, the disintegration of asbestos cement pipe, and atmospheric sources. The 1986 SDWA amendments subsequently direct EPA to regulate asbestos in public water supplies. A Maximum Contaminant Level Goal (MCLG) of 7 millions fibers exceeding 10 microns in length per liter of drinking water was promulgated in 1991 (USEPA, 1991b).

EPA recognizes that there is insufficient evidence to demonstrate that asbestos in drinking water is associated with organ-specific cancer. However, EPA believes that there is a sufficient basis to regulate asbestos as a possible human carcinogen in drinking water (Regulatory Category II). The MCLG for asbestos is primarily based on the evidence that asbestos may be associated with an increase risk of gastrointestinal cancer through occupational exposure, and animal data showing that chrysotile asbestos fibers greater than 10 microns in length may be carcinogenic by ingestion.

Asbestos is also regulated under the Federal Water Pollutants Control Act of 1972 (amended by the Clean Water Act of 1977). Under this regulation, effluent limitations and technology performance standards have been established for eleven asbestos manufacturing point sources subcategories using the best available control technology that is economically achievable (USEPA, 1974).

## Restriction or prohibition of the use of asbestos in certain products and applications

Release of asbestos fibers occurs not only in the manufacture and processing of asbestos, but also in their use and maintenance. Several regulatory actions have been taken by federal agencies to reduce asbestos exposure from certain uses or applications of asbestos-containing products or materials.

In 1973, EPA prohibited the spraying of asbestos-containing materials on buildings and structures for fireproofing and insulation purposes under the Clean Air Act (Asbestos NESHAP). The ban of the use of spray-on asbestos was later expanded to cover applications of asbestos-containing materials for decorative purposes (USEPA, 1990). In addition, the Consumer Product Safety Commission (CPSC) has banned use of asbestos-containing patching compounds (mostly for dry wall use) and artificial fireplace emberizing materials containing respirable free-form asbestos under the Consumer Product Safety Act (CPSC, 1977). In 1979, CPSC developed voluntary agreements under which hair dryer manufacturers stopped the use of asbestos heat shields.

EPA is empowered by section 6 of TSCA to ban or to restrict the manufacture, processing, distribution, use, or disposal of a chemical substance when there is a "reasonable basis" to conclude any such activity poses an

"unreasonable risk of injury to health or environment," while taking into consideration the benefits of the chemical substance for various uses and the availability of substitutes, along with economic consequences of the regulation. In 1989, EPA issued a rule, known as the Asbestos Ban and Phase Out Rule (ABPO), under the authority of TSCA, to prohibit the manufacture, importation, processing and distribution in commerce of asbestos and most asbestos-containing products in the U.S. in three stages over seven years beginning in 1990 and ending in 1996. The regulation was intended to further reduce health risks to workers and the general public from many sources of asbestos releases.

The ABPO rule, however, was challenged in the U.S. court by the asbestos industry. In October 1991, the U.S. 5th Circuit Court of Appeals vacated and remanded most of the rule. The Court's decision did not question EPA's findings on the health effects associated with asbestos exposure; rather, the decision was based on differences in legal interpretation of TSCA, the authority under which the rule was issued. The rule is still in effect for those products which were no longer in commerce when the rule was issued on July, 1989. EPA is presently considering a number of regulatory and non-regulatory actions on asbestos in response to the Court's decision.

## REGULATORY ACTIVITIES ON OTHER MINERAL FIBERS

Few actions have been taken by the U.S. regulatory authorities to prevent or limit exposures to other mineral fibers. This is primarily due to the lack of hazard and exposure information which serves as the basis for any risk reduction measures. EPA has recently identified a "respirable fibers" category as priority substances for hazard and exposure testing (USEPA, 1992). EPA is presently considering various approaches to obtain such information so that fibers of high concern can be identified for further regulatory investigation. Additionally, the following steps have been taken to address the potential risk posed by a number of specific non-asbestos fibers.

### Erionite

EPA has promulgated a significant new use rule (SNUR) under section 5(e) of TSCA for erionite fiber. Because of the known health effects of erionite, EPA believes that any use may result in significant human exposure. This rule requires persons who intend to manufacture, import, or process any article containing erionite fiber to submit a significant use notice to EPA at least 90 days before any manufacturing, importation, or processing. The required notice will provide EPA with the opportunity to evaluate the intended use and, if necessary, to prohibit or to limit that activity before it occurs (USEPA, 1991c).

### Refractory ceramic fibers

Based on animal inhalation data of RCFs submitted under section 8(e) of TSCA, EPA concluded in November 1991, that RCF may present an unreasonable risk of cancer to human health (USEPA 1991d). After conducting an accelerated review of RCF under section 4(f) of TSCA, EPA concluded that although there is

with the demolition and renovation of asbestos containing buildings. The Asbestos NESHAP does not set a quantitative fiber release level but requires work practices at demolition or renovation sites, and no "visible emissions" from any asbestos milling, manufacturing, fabricating, demolition, or renovation operation. This regulation also requires a facility survey for asbestos prior to the commencement of a demolition or renovation activity that is subject to the NESHAP.

Asbestos-containing waste is generally deposited in landfills. Asbestos is regulated as a solid waste for land disposal under the Resource Conservation and Recovery Act (RCRA) of 1976. EPA does not consider asbestos a hazardous waste under RCRA because asbestos does not pose a potential risk of leaching into groundwater. However, under expanded authority of RCRA, a few states have classified asbestos-containing waste as a hazardous waste, and these states require stringent handling and disposal procedures. The Asbestos NESHAP regulates emissions of asbestos from landfills. The rule prohibits visible emissions to the ambient air by requiring emission control procedures and appropriate work practices during collection, packaging, transportation, and disposal of friable asbestos-containing waste materials.

Asbestos is also subject to public reporting requirements for releases of hazardous substances under the Emergency Planning and Community Right-to-Know Act (EPCRA) of 1986 and the Comprehensive Emergency Response, Compensation and Liability Act (CERCLA) of 1980. EPCRA requires emergency notification to appropriate state and local authorities of any release of asbestos, and the submission of annual Toxic Release Inventory (TRI) reports to EPA and designated officials. The TRI reports include the amount of asbestos released into each environmental medium including air, water, and land (USEPA, 1988b).

### **Control of asbestos exposure in schools and buildings**

Because the health risks of school children being exposed to low levels of asbestos is a concern, Congress passed the Asbestos Hazard Emergency Response Act (AHERA) in 1986 as a Subchapter II of TSCA to protect school children and employees from exposure to asbestos in school buildings. The Act required EPA to develop regulations creating a comprehensive framework for dealing with asbestos in public and nonprofit private elementary and secondary schools. To implement AHERA, EPA issued the Asbestos-Containing Materials in School Rule in 1987 (USEPA, 1987b). The AHERA school rule requires local education agencies to identify asbestos-containing materials in school buildings and take appropriate action to control release of asbestos, including inspections for asbestos, development of management plans, and to carry out the plan in a timely fashion. The school rule also requires the development of an asbestos operations and maintenance plan for schools where asbestos materials remain in place. The AHERA school regulations do not require schools to remove asbestos-containing materials.

AHERA also requires that EPA conduct a study to determine (1) the extent and condition of asbestos in public and commercial buildings; and (2) whether

public and commercial buildings should be subject to the same inspection and response action requirements that apply to school buildings under the AHERA school rule. In response to Congressional mandate, in February 1988, EPA completed a study known as "EPA Study of Asbestos-Containing Materials in Public Buildings—A Report to Congress" (USEPA, 1988c).

EPA's study determined that friable asbestos-containing materials can be found in about one-fifth of the public and commercial buildings in the U.S. Two-thirds of these asbestos-containing buildings have at least some asbestos that is already damaged. Although EPA believed that asbestos in commercial buildings represents a potential health hazard that deserves attention, EPA did not recommend a comprehensive regulatory inspection and abatement program such as was implemented for school buildings. This was because there is only a limited supply of the accredited professionals and laboratories that are needed for the implementation of AHERA school rule, which has priority attention. Rather, EPA recommended to Congress that the Agency work during the next three years to enhance the nation's technical capability in asbestos by helping building owners better select and apply appropriate asbestos control and abatement actions in their buildings. To carry out that recommendation, EPA published a comprehensive asbestos guide known as "Managing Asbestos in Place" in July 1990 (USEPA, 1990b). This publication provides detailed and up-to-date instruction to building owners to help them successfully manage asbestos-containing materials in place.

On March 6, 1991, EPA published "An Advisory to the Public on Asbestos in Buildings" to provide guidance to the public for reducing asbestos exposure in buildings and to clarify EPA's policies regarding asbestos in schools and buildings (USEPA, 1991a). The advisory is in the form of five major facts that the Agency presented in congressional testimony. EPA concluded that on the basis of limited data, prevailing asbestos levels in buildings with asbestos management programs were very low. Although the data are not conclusive, available information suggests that health risks to building occupants are likely to be low when their buildings have active asbestos management programs. EPA recommended in-place management to control fiber release when the asbestos-containing materials are not significantly damaged. EPA also pointed out that removal of asbestos is not always the best alternative from a public health perspective. Improperly performed removal of asbestos can result in a very high level of exposure for building occupants. When removal is deemed necessary, i.e., when asbestos containing materials are damaged beyond repair, careful procedures to prevent exposure to the public both and during and after the removal are mandated.

EPA's findings concerning health risks to building occupants are consistent with conclusions reached by the Health Effects Institute—Asbestos Research (HEI, 1991). EPA and HEI recognized that building workers (i.e., service and custodial workers) may face greater health risks than building occupants, if they are not properly trained and protected, since they are more likely to be transiently exposed to higher levels of asbestos. OSHA and EPA have agreed that OSHA will take the lead in pursuing regulation to address these potential risks, and both agencies will work cooperatively to this end.

sufficient evidence to classify RCF as a probable human carcinogen, exposure data are inadequate to determine whether or not RCFs pose an unreasonable health risk to workers. However, there was sufficient basis to support a concern for RCF and to initiate a regulatory investigation of RCF. Since there is a need to develop additional worker exposure data, EPA considered requiring the testing by promulgating test rules or by adopting enforceable consent agreements under section 4 of TSCA. In light of the manufacturers' willingness to work with EPA on the development of an exposure testing program to monitor workplace exposures (i.e., manufacturing, fabrication, processing, installation, and removal), EPA signed an enforceable testing consent order with the Refractory Ceramic Fibers Coalition (RCFC) in May 1993 (USEPA, 1993).

In addition to developing the exposure monitoring consent order with EPA, RCFC has developed and implemented a Product Stewardship Program which includes an implementation of workplace exposure control measures and a 1 f/ml industry recommended exposure guideline. Results from the exposure testing consent order should help determine the effectiveness of industry's stewardship of RCF.

OSHA has also proposed a 1 f/ml 8-hour TWA limit for respirable RCF for the construction, maritime, agriculture, and general industry. The proposed exposure limit is based on non-malignant respiratory disease, although OSHA has pointed out that the proposed limit will also increase the protection of workers from the potential carcinogenic effects (OSHA, 1992).

### Glass fiber and mineral wool

Title III of the 1990 Clean Air Act amendments establishes a control technology-based program to reduce stationary source emissions of hazardous air pollutants. Man-made mineral fibers (including glass fibers, rock wool, and slag wool fibers) have been designated as hazardous air pollutants under section 112 (b) of the 1990 CAA amendments (CAA, 1990). EPA is in the process of establishing emissions standards for this group of substances.

OSHA has also proposed, under section 6(a) of OSH Act, a 1 f/ml 8-hour TWA limit for the respirable fibers of fibrous glass, rock wool, and slag wool for the construction, maritime, agriculture, and general industry. OSHA believes that this limit will protect worker from the risk of nonmalignant respiratory disease (OSHA, 1992).

### CONCLUSIONS

Extensive regulations and guidelines have been established by several U.S. federal agencies to control or to limit the exposure of asbestos to humans. In contrast, only limited activities have been focused on other mineral fibers. However, it is generally recognized that there is an adequate basis to support a concern for respirable fibers, particularly those which are durable. Hence, there is a need to develop a comprehensive strategy for reducing risks from exposures to all respirable fibers. Components of such a strategy should include the practice of pollution prevention, development and implementation of product stewardship

program, design of safer products (e.g., development of non-respirable fibrous products), the conduct of health effects research and testing, and exposure monitoring. Cooperative efforts among the federal agencies, industrial sectors, and public interest groups are necessary to achieve this goal, which is aimed at protecting the public from an unreasonable risk of injury.

### REFERENCES

- Agency for Toxic Substances and Disease Registry (ATSDR) (1990) Toxicological profile for asbestos. U.S. Department of Human and Health & Human Services, TP-90-04.
- Clean Air Act Amendments (CAA) (1990) Public Law 101-549; 101st Congress, November 15, 1990.
- Consumer Product Safety Commission (CPSC) (1977) Consumer patching compounds and artificial emberizing materials (embers and ash) containing respirable free-form asbestos; Final rule. Fed. Register 42, 63354-63365.
- Health Effects Institute (HEI) (1991) Asbestos in public and commercial buildings: A literature review and synthesis of current knowledge. Health Effects Institute-Asbestos Research, Cambridge, Mass.
- IRIS (1992) Integrated Risk Information System. Refractory ceramic fibers: Carcinogenicity assessment 09/01/92. U.S. Environmental Protection Agency, Washington, D.C.
- International Agency for Research on Cancer (IARC) (1987) Silica and some silicates. Monographs on the evaluation of carcinogenic risk of chemicals to humans, Vol. 42, Lyon, France.
- International Agency for Research on Cancer (IARC) (1988) Man-made mineral fibres and radon. Monographs on the evaluation of carcinogenic risks to humans, Vol. 43, Lyon, France.
- International Programme on Chemical Safety (IPCS) (1986) Asbestos and other natural mineral fibres. Environmental Health Criteria 53. World Health Organization, Geneva.
- International Programme on Chemical Safety (IPCS) (1988) Man-made mineral fibres. Environmental Health Criteria 77. World Health Organization, Geneva.
- Mine Safety and Health Administration (MSHA) (1977) 30 CFR Part 56 et al.
- Mine Safety and Health Administration (MSHA) (1989) Air quality, chemical substances, respiratory protection standards; proposed rule. Fed. Register 54, 35760-35852.
- Occupational Safety and Health Administration (OSHA) (1972) Standard for exposure to asbestos dust. Fed. Register 37:11318-11322.
- Occupational Safety and Health Administration (OSHA) (1986) Occupational exposure to asbestos, tremolite, anthophyllite, and actinolite; final rules. Fed. Register 51, 22612-22790.
- Occupational Safety and Health Administration (OSHA) (1992) Air contaminants; Proposed rule. Fed. Register 57, 26002-26601.
- U.S. Environmental Protection Agency (USEPA) (1974) Effluent Guidelines and Standards; Asbestos manufacturing point source category. CFR Part 427.
- U.S. Environmental Protection Agency (USEPA) (1986) Airborne asbestos health assessment update. EPA/600/8-84/003F.
- U.S. Environmental Protection Agency (USEPA) (1987a) EPA worker protection rule. 40 CFR 763 Subpart G.
- U.S. Environmental Protection Agency (USEPA) (1987b) EPA Asbestos Hazard Emergency Response Act (AHERA) Regulations. 40 CFR 763 Subpart E.
- U.S. Environmental Protection Agency (USEPA) (1988a) Health hazard assessment of nonasbestos fibers. OPTS-62036. By V.T. Vu, Office of Toxic Substances, U.S. Environmental Protection Agency, Washington, D.C.
- U.S. Environmental Protection Agency (USEPA) (1988b) Toxic chemical release reporting. Fed. Register 53, 4500-4539.
- U.S. Environmental Protection Agency (USEPA) (1988c) EPA study of asbestos-containing materials in public buildings: A report to Congress. USEPA, Washington, D.C.
- U.S. Environmental Protection Agency (USEPA) (1989) Asbestos: Manufacture, importation, processing, and distribution in commerce prohibitions; Final rule. Fed. Register 54, 29460-29513.
- U.S. Environmental Protection Agency (USEPA) (1990a) National Emission Standards for Hazardous Air Pollutants (NESHAP). 40 CFR 61 Subpart M.
- U.S. Environmental Protection Agency (USEPA) (1990b) Managing asbestos in place- A building owner's guide to operations and maintenance programs for asbestos-containing materials. 20T-2003.
- U.S. Environmental Protection Agency (USEPA) (1991a) An advisory to the public on asbestos in buildings: The facts about asbestos in buildings. Washington, D.C.
- U.S. Environmental Protection Agency (USEPA) (1991b) National primary drinking water regulations: Final rule. Fed. Register 56, 3526-3597.

- U.S. Environmental Protection Agency (USEPA) (1991c) Erionite fiber; Significant new use of a chemical substance. Fed. Register 56, 56470-56472.
- U.S. Environmental Protection Agency (USEPA) (1991d) Refractory Ceramic Fibers; Initiation of priority review. Fed. Register 56, 58693-58694.
- U.S. Environmental Protection Agency (USEPA) (1992) Master Testing List. Office of Prevention, Pesticides and Toxics, USEPA, Washington, D.C.
- U.S. Environmental Protection Agency (USEPA) (1993) Testing consent order for refractory ceramic fibers. Fed. Register 58, 28517-28520.
- Vu, V.T. (1992) Refractory ceramic fibers: EPA's risk assessment and regulatory status. Proceedings of the Toxicology Forum 1992 Annual Winter Meeting. Toxicology Forum Inc., Washington, D.C., p. 400-416.
- Vu, V.T., and Dearfield, K.L. (1993) Biological effects of fibrous materials in experimental studies and related regulatory aspects. In Warheit DB (ed.) Fiber Toxicology. Academic Press, New York, p. 449-492.
- Vu, V.T. (1993) Assessment of the potential health effects of natural and man-made fibers and their testing needs: perspectives of the U.S. Environmental Protection Agency. Proc. 4th Int'l Inhalation Symp., in press.

## GLOSSARY

The following glossary contains several biological and geological terms that may be unfamiliar to some readers. A more thorough listing of terms can be found in a general scientific dictionary, such as *Dictionary of Scientific and Technical Terms* (1989, 4th edition, S.P. Parker, Editor, McGraw Hill, New York, 2138 pp.), or in dictionaries specific to each of the disciplines (e.g., *Glossary of Geology*, 1980, 2nd edition, R.L. Bates and J.A. Jackson, Editors, American Geological Institute, Falls Church, Virginia, 751 pp.; *Stedman's Medical Dictionary*, 1990, 25th edition, W.R. Hensyl, Editor, Williams and Wilkins, Baltimore, Maryland, 1784 pp.). Many of the definitions below are modified from these sources. Accepted mineral species names and formulae can be found in the *Mineral Reference Manual* (1991, E.H. Nickel and M.C. Nichols, van Nostrand Reinhold, New York, 250 pp.), and we have generally followed their usage. However, in some cases, errors in the *Mineral Reference Manual* have been corrected here. The editors assume ultimate responsibility for the correctness of the following definitions. However, we acknowledge the assistance of many in developing this glossary, including the authors of chapters in this book and H.C.W. Skinner. Many of the definitions below use words that are also defined in the glossary, and these words are generally italicized.

**a-axis:** One of the three principle axes used to describe the coordinate system of a crystal structure. See *crystallographic axes*.

**accessory mineral:** Any mineral that is present in a rock but is not essential to classifying the rock. Generally accessory minerals are present in minor quantities.

**acicular:** Said of a crystal that is needlelike in form. A high aspect ratio mineral particle formed during growth or crushing. See *asbestiform*, *fibrous*, *prismatic*, *equant*, *tabular*.

**actinolite:** An amphibole with the ideal composition  $\text{Ca}_2(\text{Mg}, \text{Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ . Actinolite is a species in the Mg-Fe<sup>2+</sup> series, tremolite-ferro-actinolite, with  $0.9 > \text{Mg}/(\text{Mg} + \text{Fe}^{2+}) > 0.5$ . See *amphibole*, *ferro-actinolite*, *tremolite*.

**activation energy:** The additional energy required to allow a system to proceed from one energy state to another, e.g., to make a reaction proceed.

**active oxygen species:** Oxygen free radicals. Reactive metabolites or reduced species of oxygen that can react with cellular targets, including DNA. These species possess a non-equilibrium number of electrons (i.e., they possess an unpaired electron), such that the species is unstable and can function as either an electron donor/acceptor or a proton donor/acceptor. See *hydroxyl radical*, *superoxide*.

**additive:** The condition when two or more agents induce a biological response that is the sum of the weighted biological responses of each agent individually.

**aeolian:** See *eolian*.

**AEM:** Analytical electron microscopy. This is typically done using a transmission electron microscope equipped with a capability such as energy-dispersive spectrometry. By performing AEM with a transmission electron microscope, additional important mineralogical information may be obtained, such as electron diffraction information, particle morphology, microstructures, etc.

**AES:** Auger electron spectroscopy.

**AFM:** Atomic force microscopy or atomic force microscope.

**agate:** A type of microcrystalline quartz.

**akaganeite:**  $\beta\text{-FeOOH}$ . See *lepidocrocite* and *goethite*.

**alkali feldspar:** A feldspar with an ideal composition of  $(\text{K}, \text{Na})\text{AlSi}_3\text{O}_8$ .